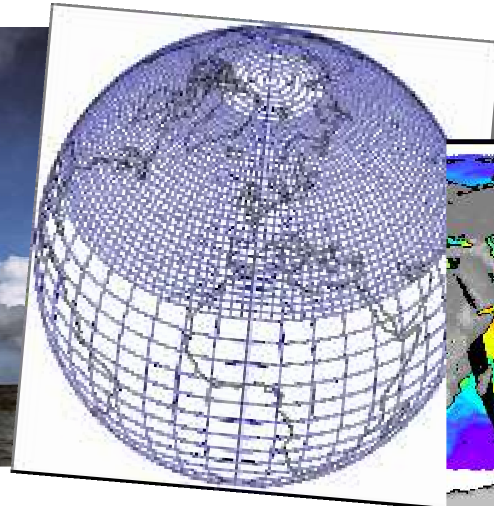
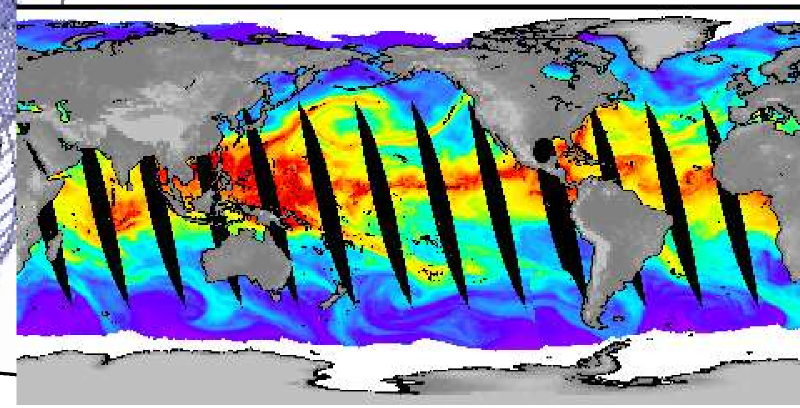




Current and future changes in the global water cycle

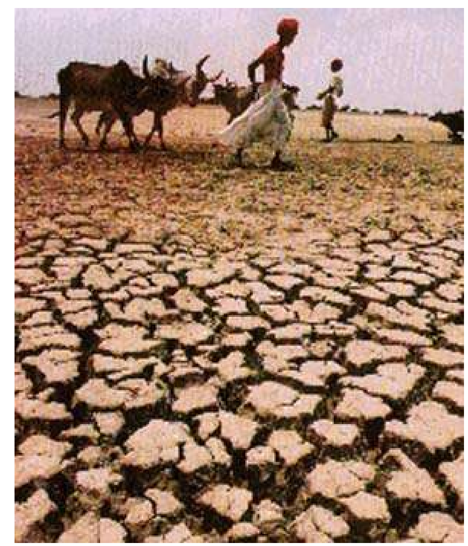
Richard P. Allan
Department of Meteorology, University of Reading

Thanks to Brian Soden, Viju John, William Ingram, Peter Good, Igor Zveryaev and Mark Ringer

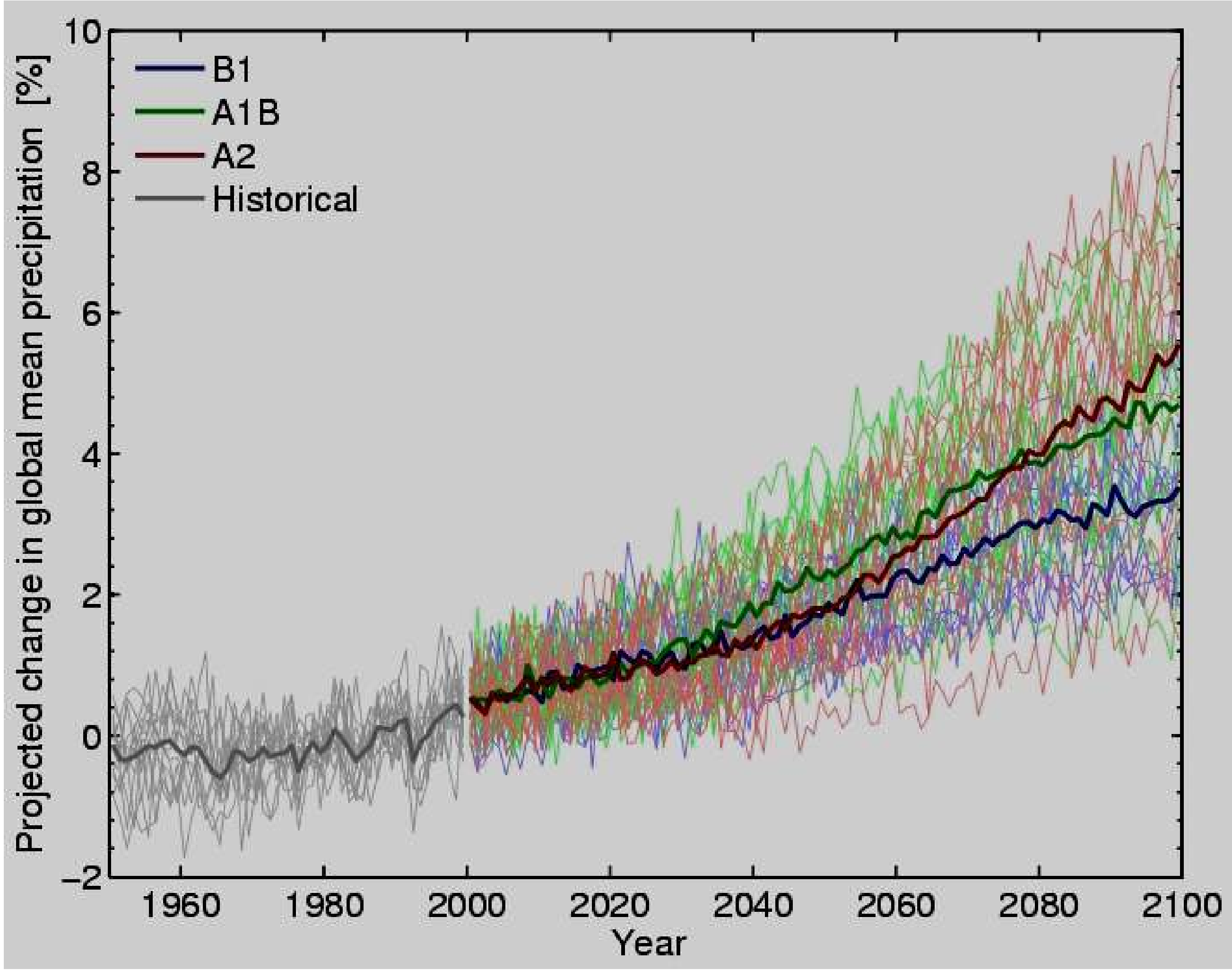
http://www.met.reading.ac.uk/~sgs02rpa
r.p.allan@reading.ac.uk

Introduction

"Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems."
IPCC (2008) Climate Change and Water



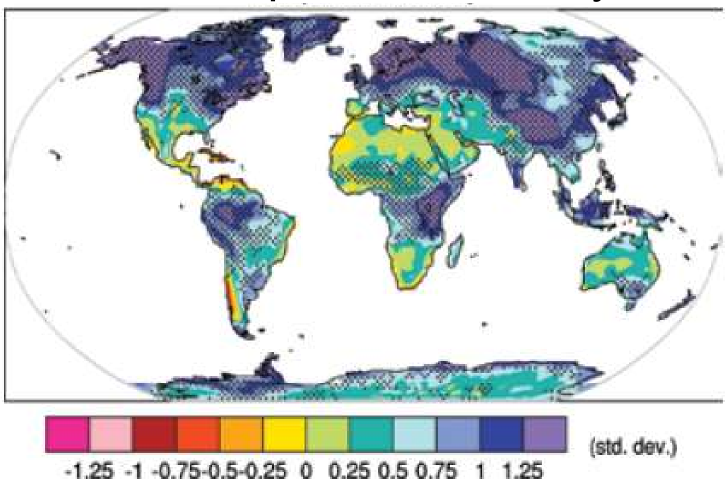
But how should global precipitation respond to climate change?



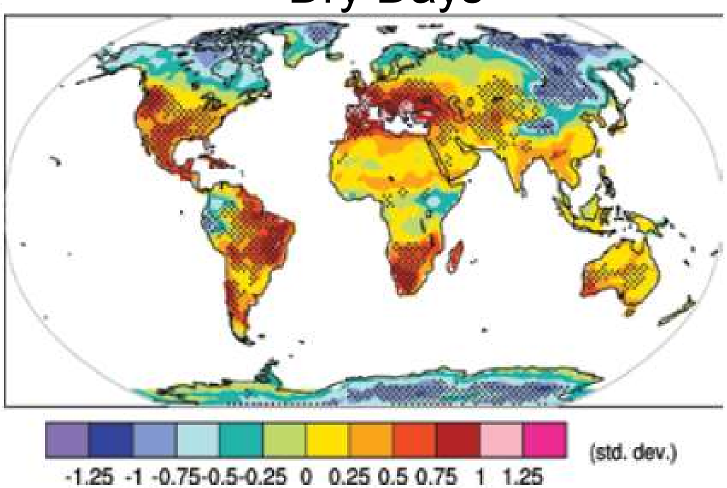
Hawkins and Sutton (2010) Clim. Dyn.

Climate model projections (IPCC 2007)

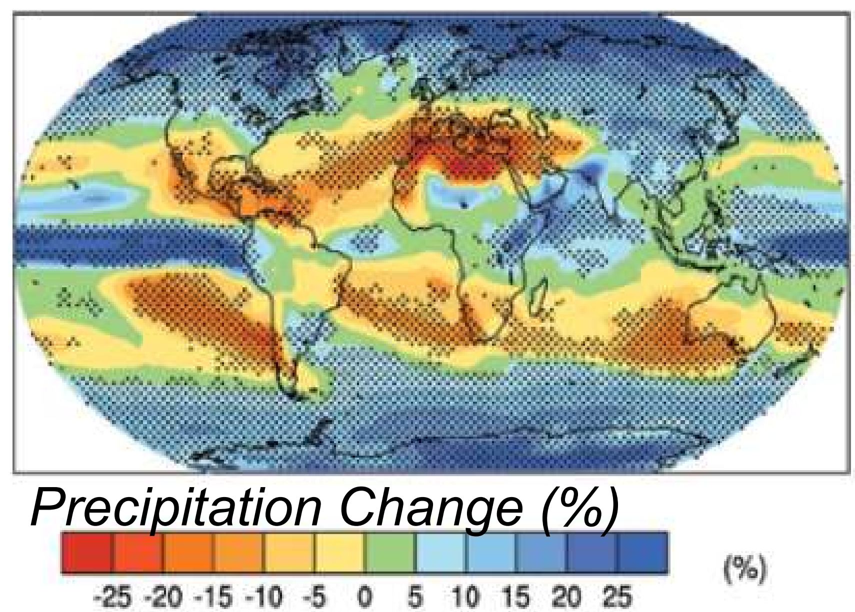
Precipitation Intensity



Dry Days

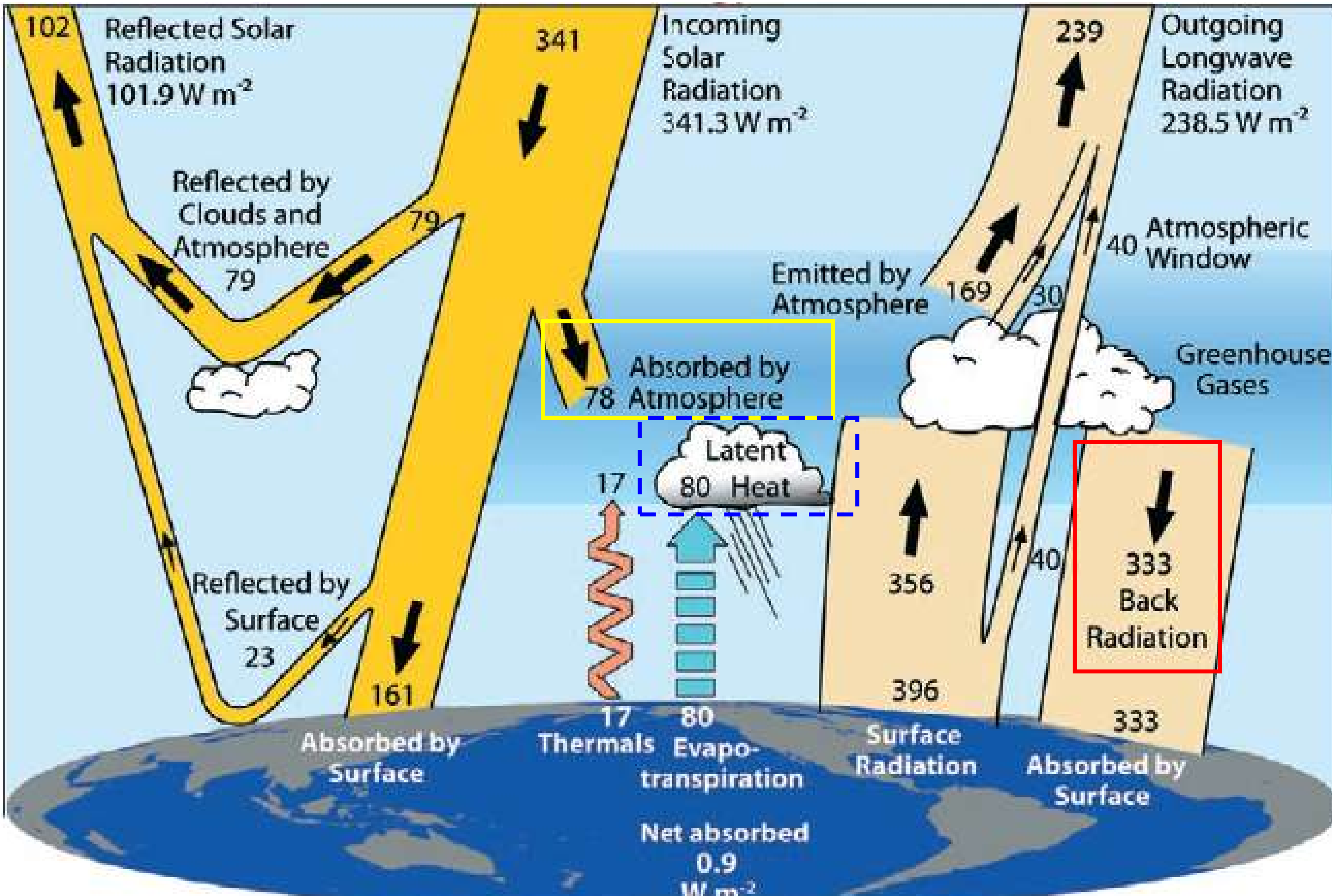


- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??



Precipitation Change (%)

Physical basis: energy balance



Trenberth et al. (2009) BAMS

What rate of rainfall?

Net radiative cooling, $R_{atm} \approx 115\ Wm^{-2}$

Sensible heating of atmosphere, $SH \approx 15\ Wm^{-2}$

If this balances Latent Heating from precipitation, P:

$P = R_{atm} - SH \approx 100\ Wm^{-2} = 100\ J\ s^{-1}\ m^{-2}$

Assume density of water, $\rho_w = 1000\ kgm^{-3}$ and latent heating all from condensation, $L = 2.5 \times 10^6\ J\ kg^{-1}$:

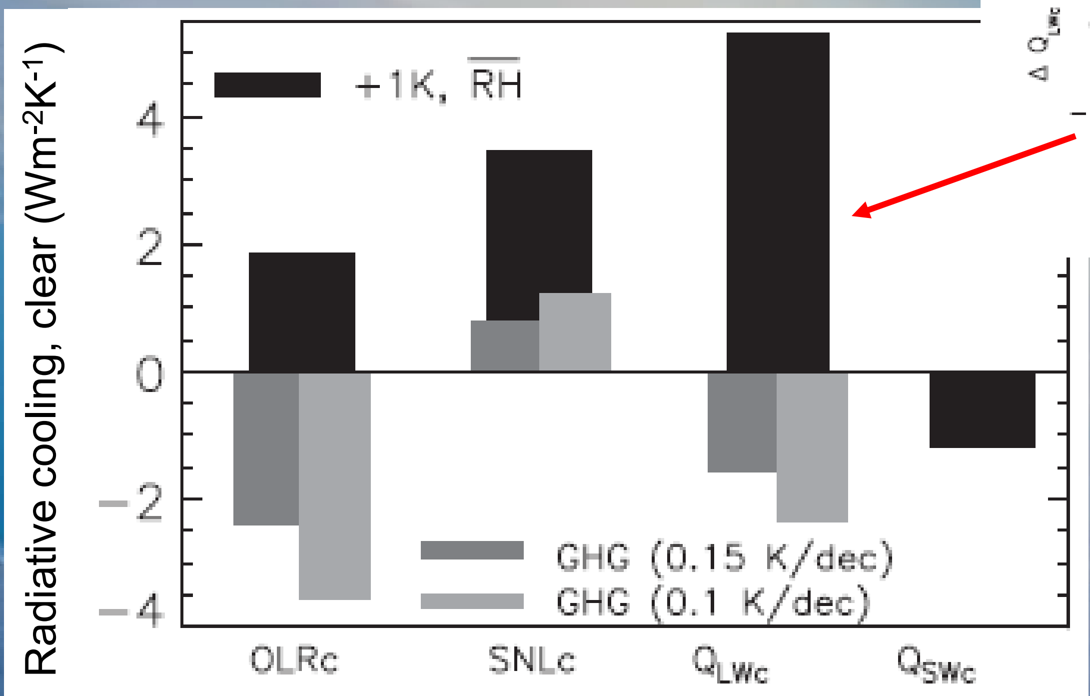
Rate of condensation: $P/\rho_w L = 100/2.5 \times 10^9 = 4 \times 10^{-8}\ ms^{-1}$

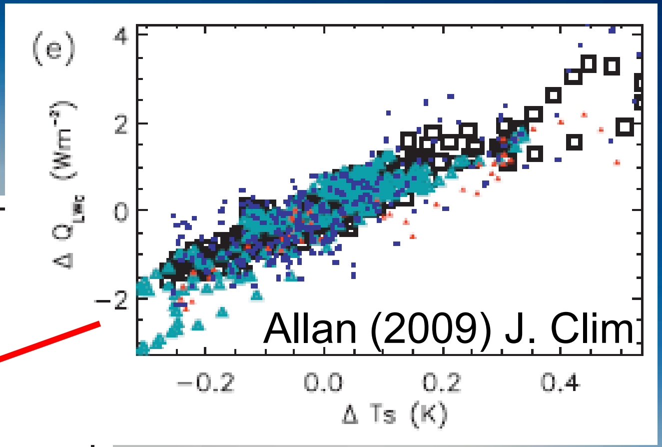
$= 3.4$ mm/day

A warming atmosphere radiatively cools more effectively…

Models simulate robust response of clear-sky radiation to warming (~2 $Wm^{-2}K^{-1}$) and a resulting increase in precipitation to balance (~2 $\%K^{-1}$)

e.g. Allen and Ingram (2002) Nature, Lambert and Webb (2008) GRL

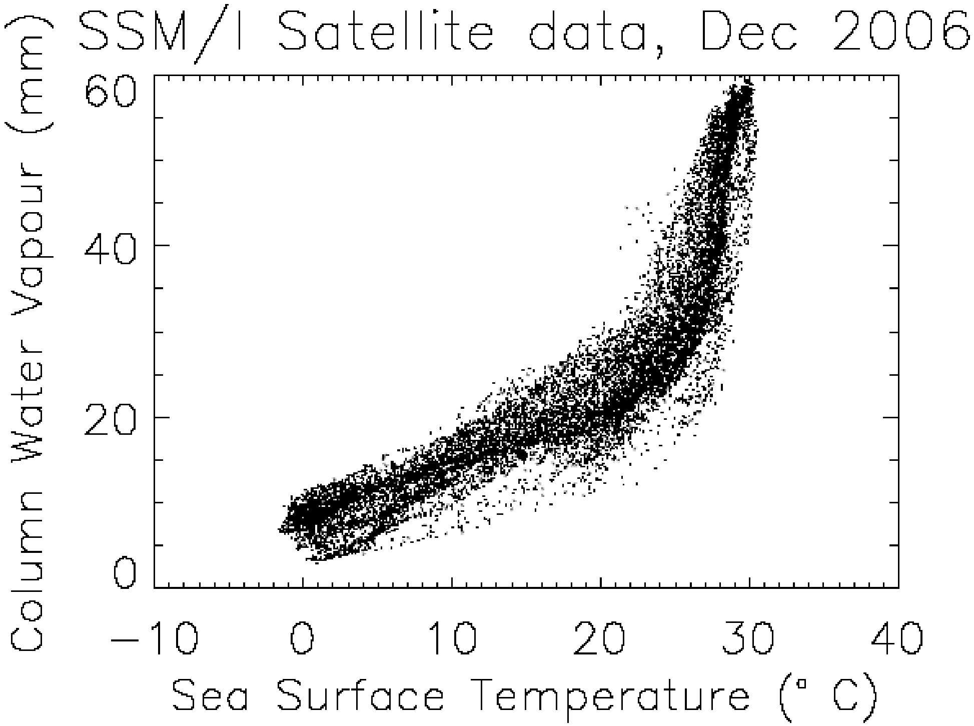




$$\frac{dP}{dTs} \sim \frac{1}{\rho_w L} \frac{dQ}{dTs}$$

Physical basis: Clausius Clapeyron

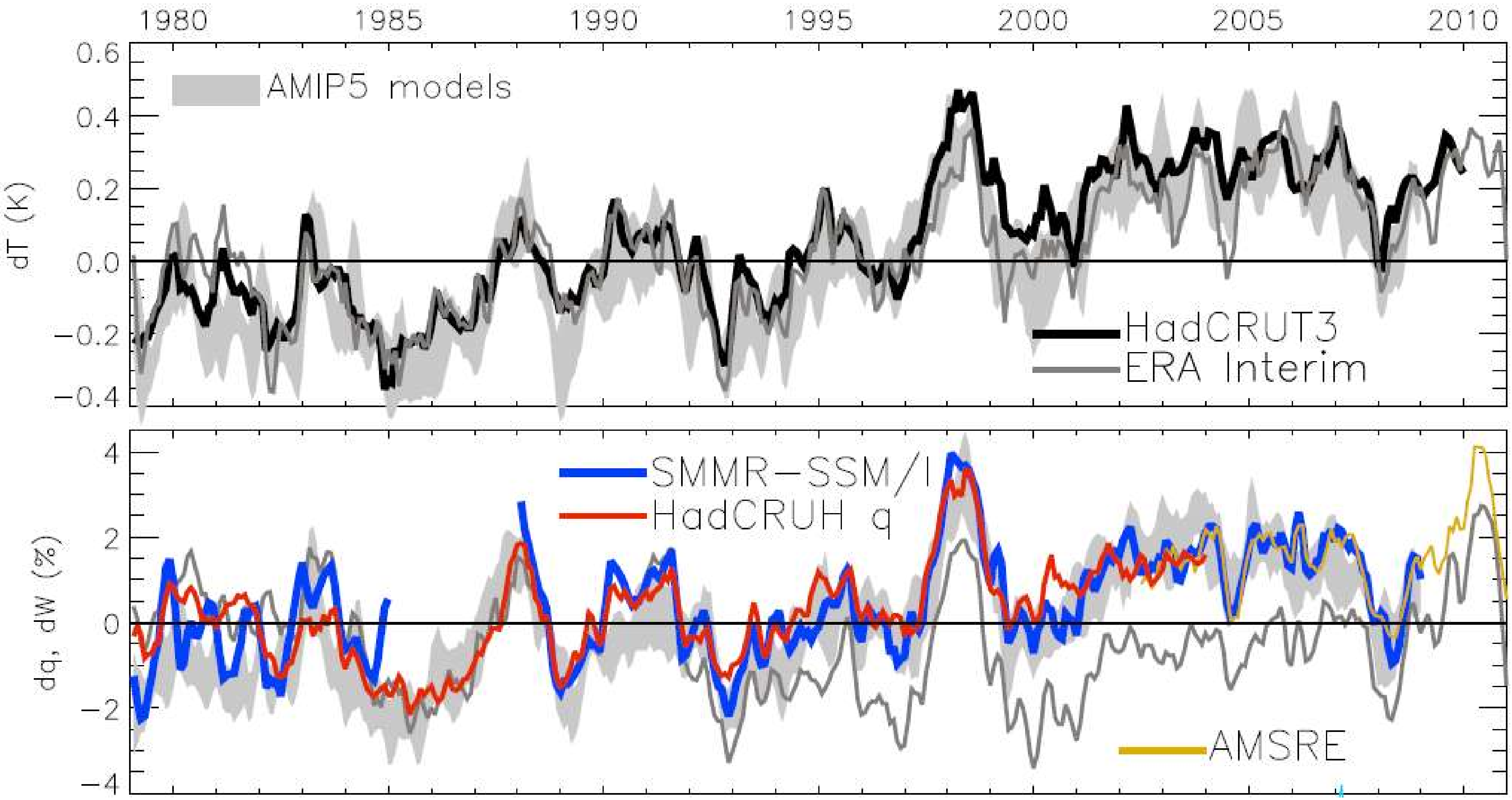
$$\frac{1}{q_s}\frac{dq_s}{dT} \approx \frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2} = \begin{cases} 0.14K^{-1} & T = 200K \\ 0.07K^{-1} & T = 273K \\ 0.06K^{-1} & T = 300K \end{cases}$$



- Strong constraint upon low-altitude water vapour over the oceans
- Land regions?

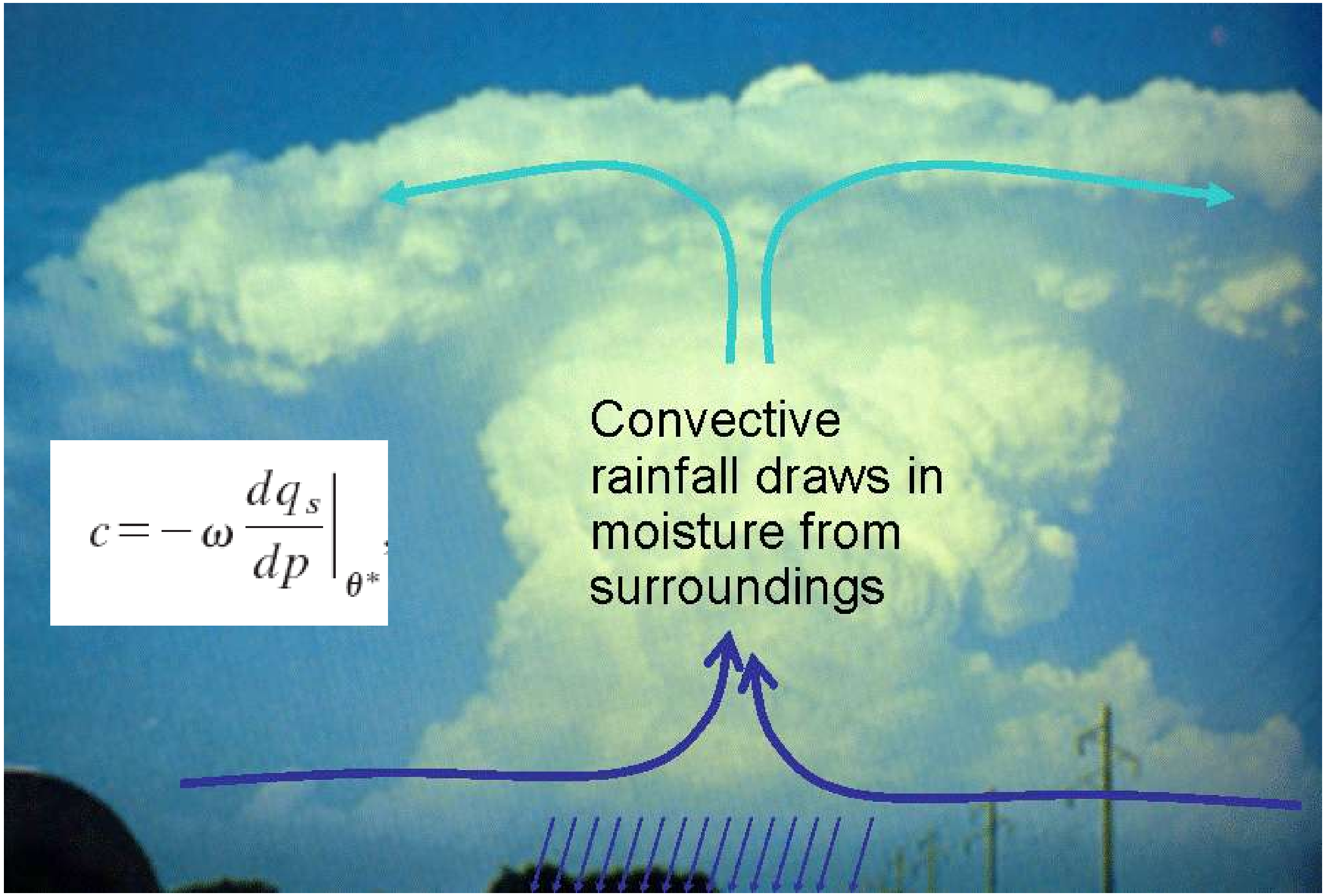
e.g. Allan (2012) *Surv. Geophys. in press*

Global changes in water vapour



Updated from O'Gorman et al. (2012) Surv. Geophys; see also John et al. (2009) GRL

Extreme Precipitation



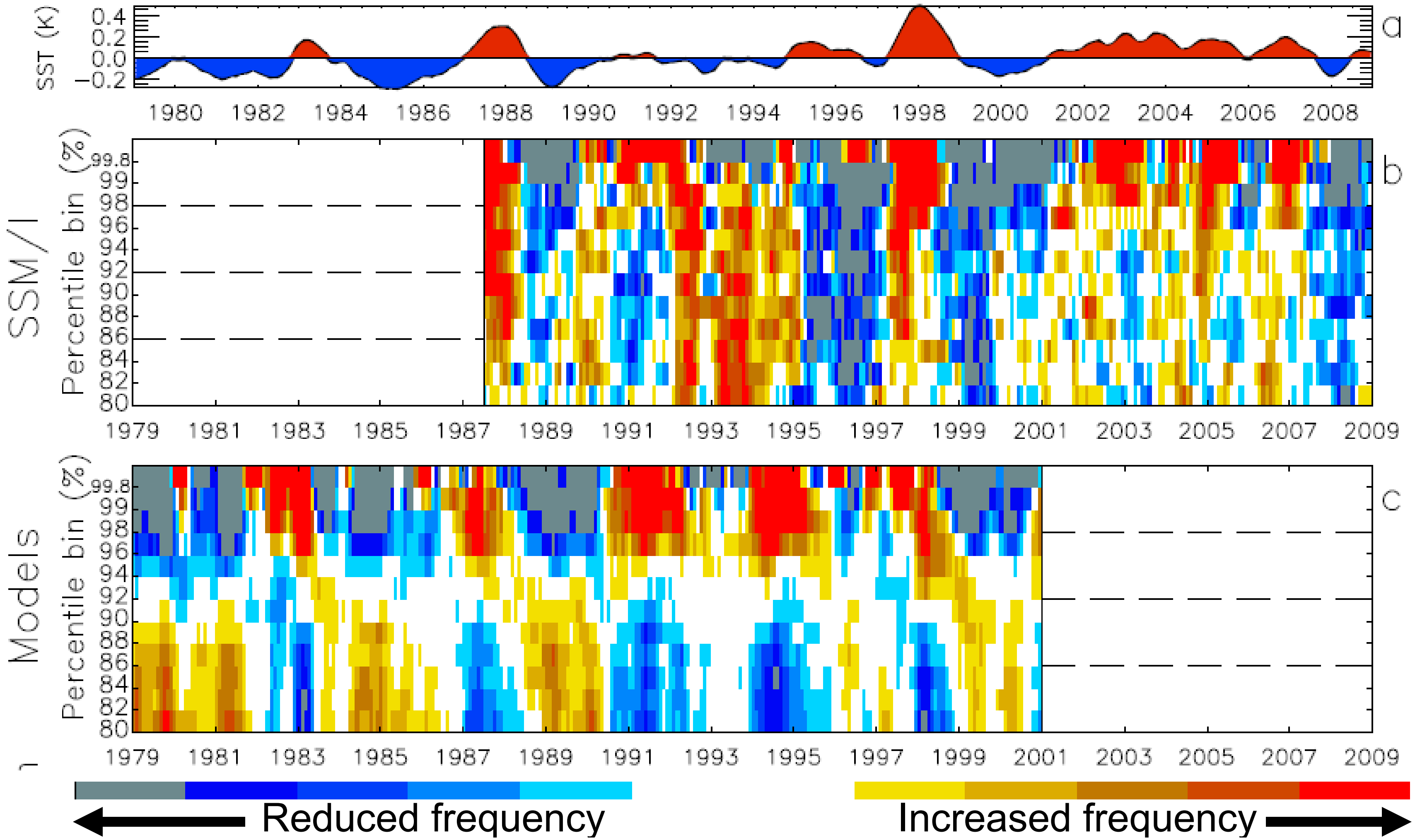
$$c = -\omega \frac{dq_s}{dp}\bigg|_{\theta^*}$$

- Large-scale rainfall events fuelled by moisture convergence
  - e.g. Trenberth et al. (2003) *BAMS. But see Wilson and Toumi (2005) GRL*

→ Intensification of rainfall (~7%/K?)

O'Gorman and Schneider (2009) PNAS; Gastineau and Soden (2009) GRL

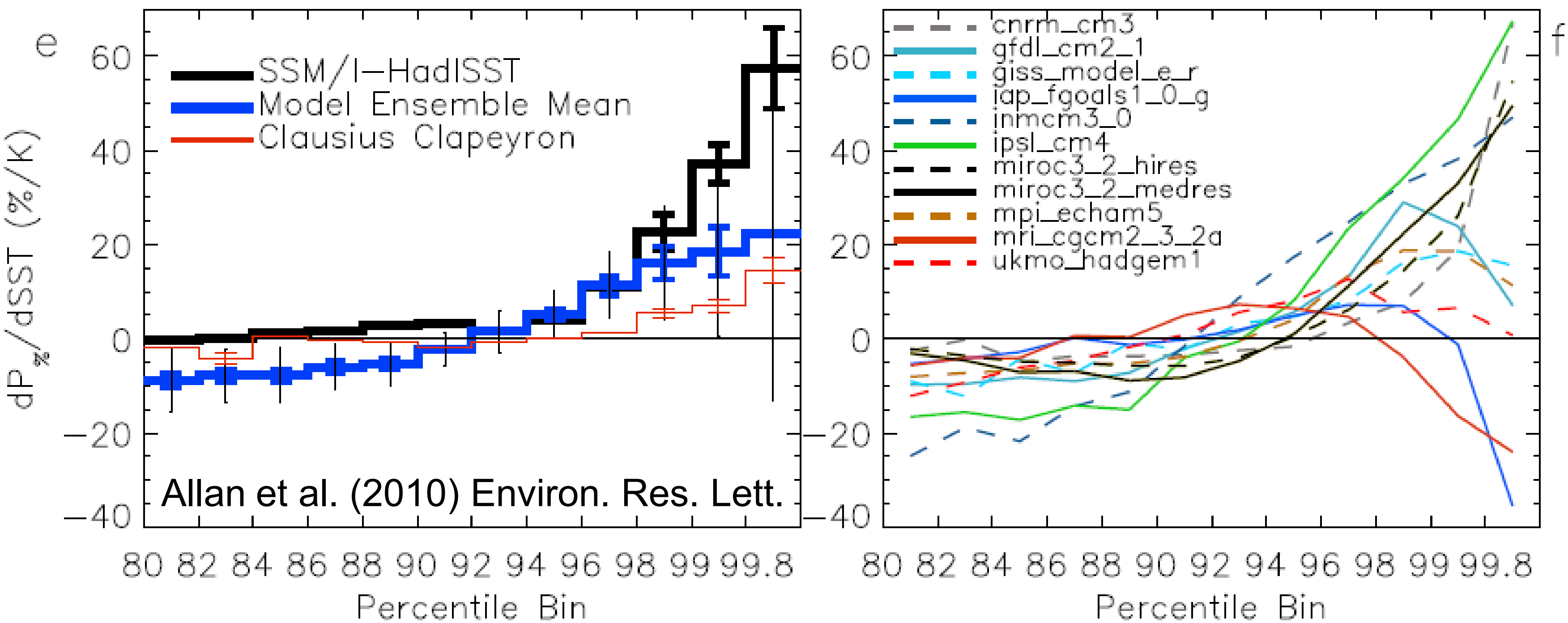
Increases in the frequency of the heaviest rainfall with warming: daily data from models and microwave satellite data (SSM/I)



Allan and Soden (2008) Science; Allan et al. (2010) Environ. Res. Lett.

Observed and Simulated responses in extreme Precipitation

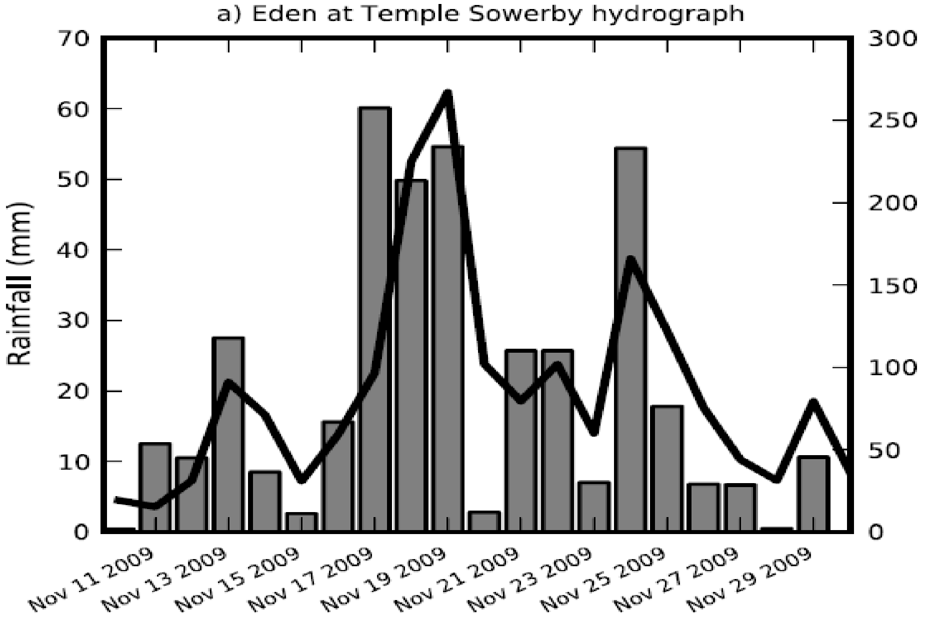
- Increase in intense rainfall with tropical ocean warming
- SSM/I satellite observations at upper range of models

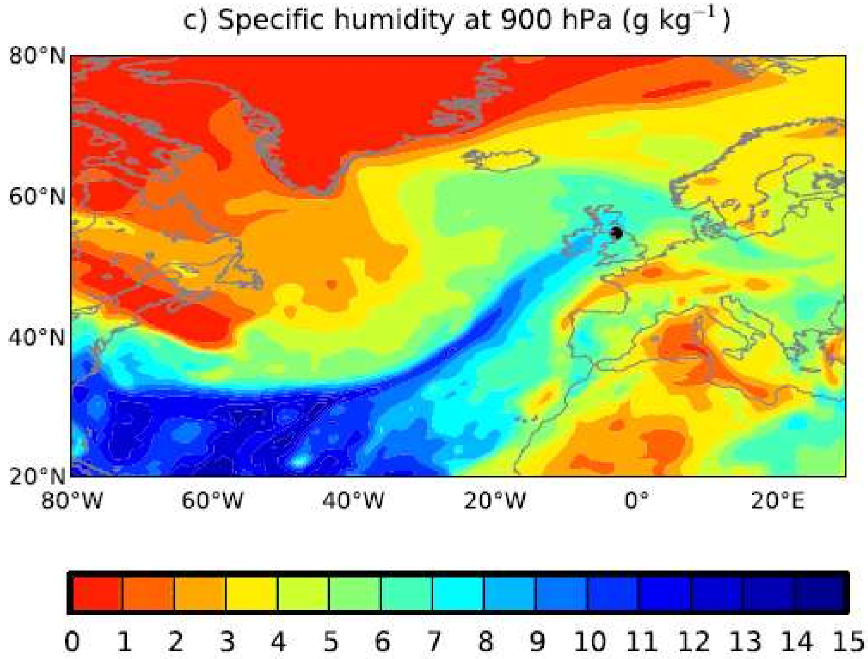


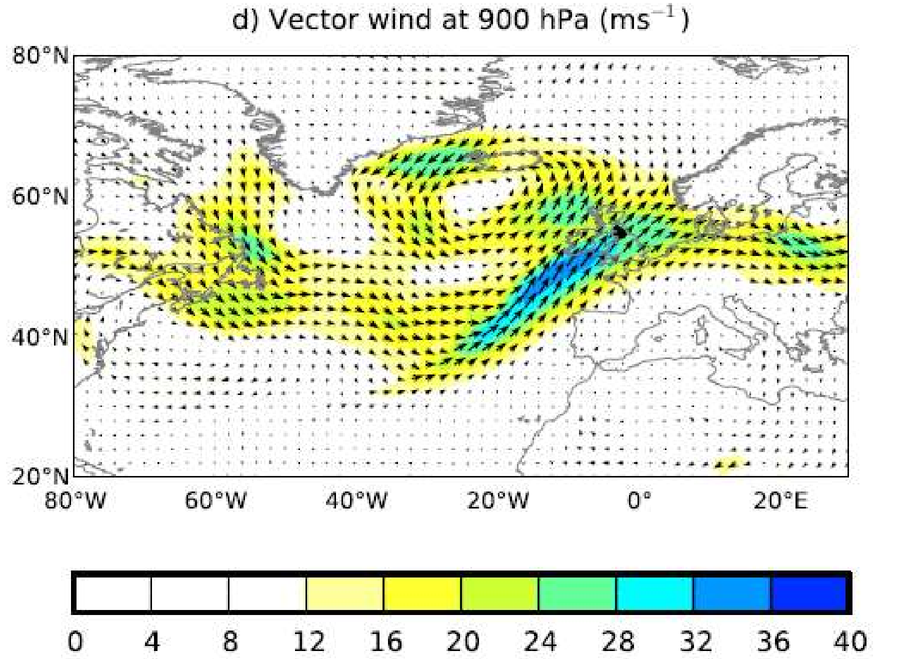
Tropical response uncertain: O'Gorman and Schneider (2009) PNAS….
but see also: Lenderink and Van Meijgaard (2010) ERL; Haerter et al. (2010) GRL

Extreme precipitation & mid-latitude Flooding

- Atmospheric Rivers or moisture conveyors
- Nov 2009 Cumbria floods

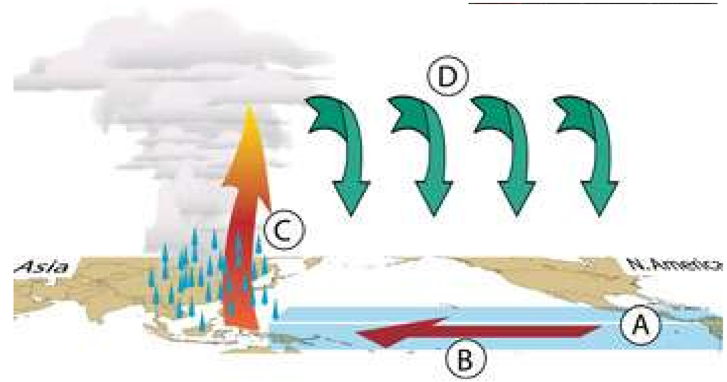




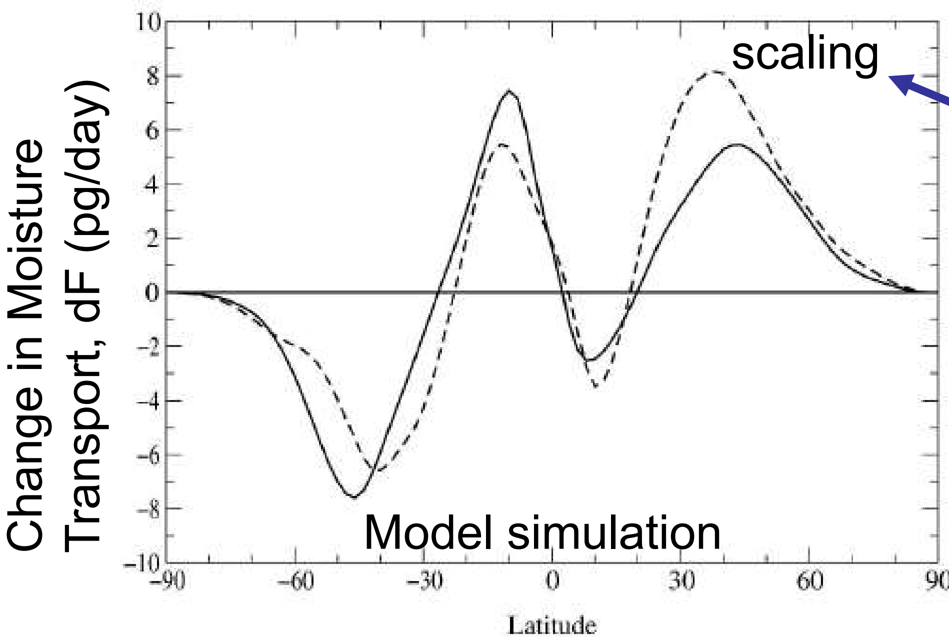


Lavers et al. (2011) GRL in press

Physical Basis: Moisture Balance



$P\text{-}E \sim (\nabla \cdot (u\, q))$ (units of s^{-1}; scale by $(p/g\rho_w)$ for units of mm/day)



$$\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T.$$

$$\alpha \approx 0.07\ \mathrm{K}^{-1}$$

If the flow field remains relatively constant, the moisture transport scales with low-level moisture.

Held and Soden (2006) J Climate

Projected (top) and estimated (bottom) changes in P-E

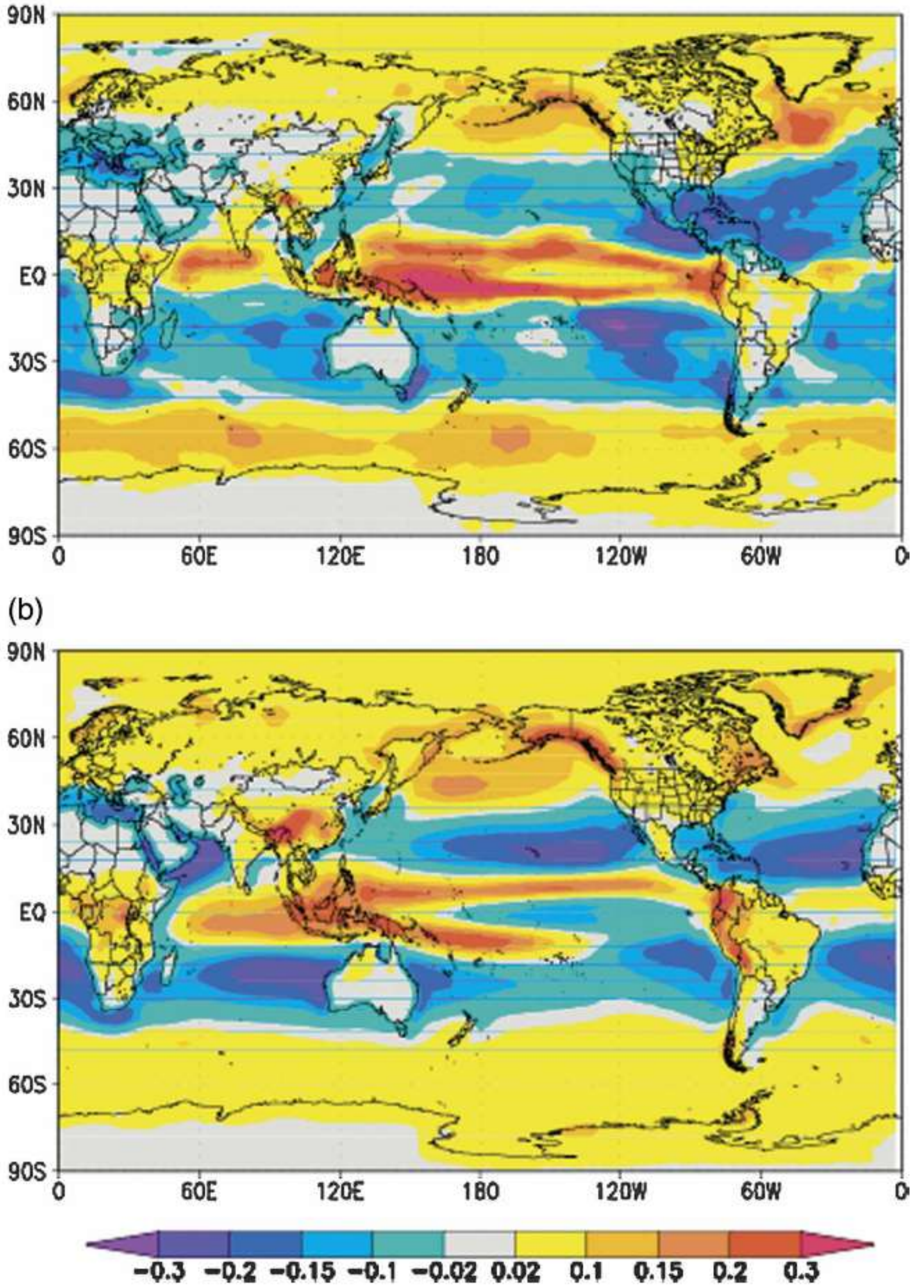


FIG. 7. The annual-mean distribution of $\delta(P-E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

$$\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T.$$

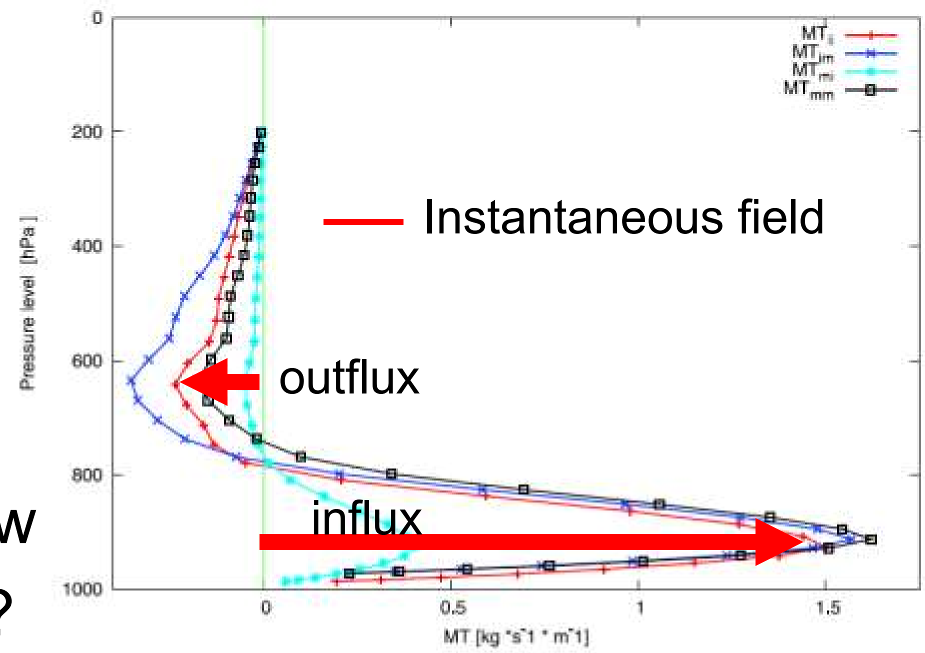
$$\delta(P-E) = -\nabla \cdot (\alpha \delta T F). \sim \alpha \delta T (P-E).$$

$$\alpha \approx 0.07\ \mathrm{K}^{-1}$$

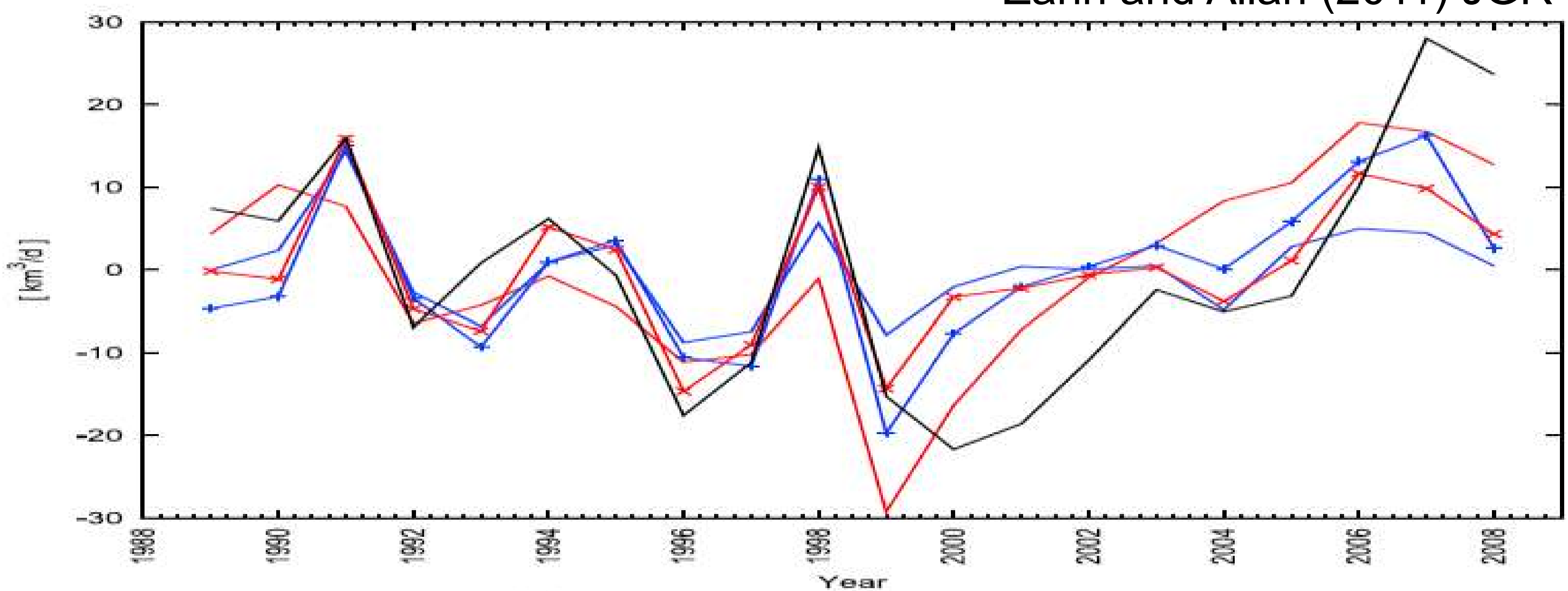
Held and Soden (2006) J Climate

Moisture transports from ERA Interim

- Moisture transport into tropical ascent region
- Significant mid-level outflow
- 2000s: increases in inflow?



Zahn and Allan (2011) JGR



(a) yearly MT anomaly

Changes in tropical circulation?

- Wind-driven changes in sea surface height
  Merrifield (2011) J Clim
  http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI3932.1
- Increases in satellite altimeter wind speed?

Young et al. (2011) Science

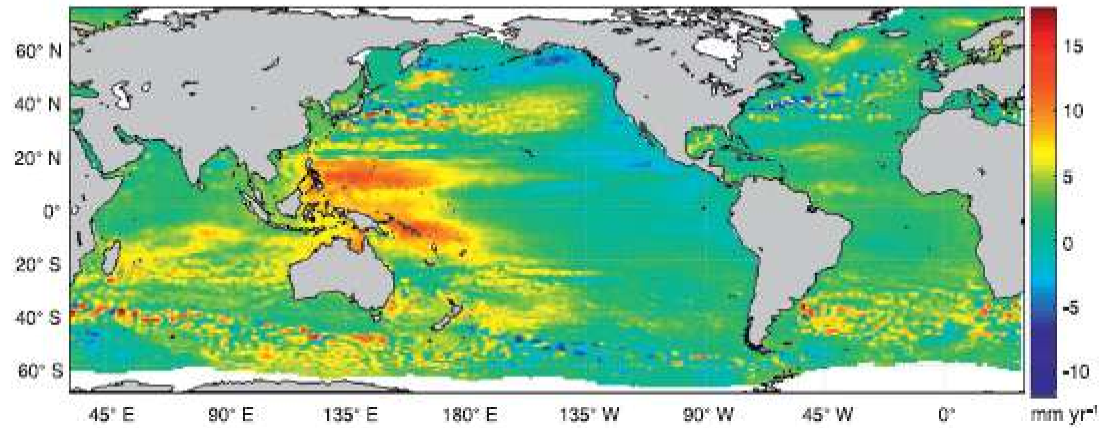
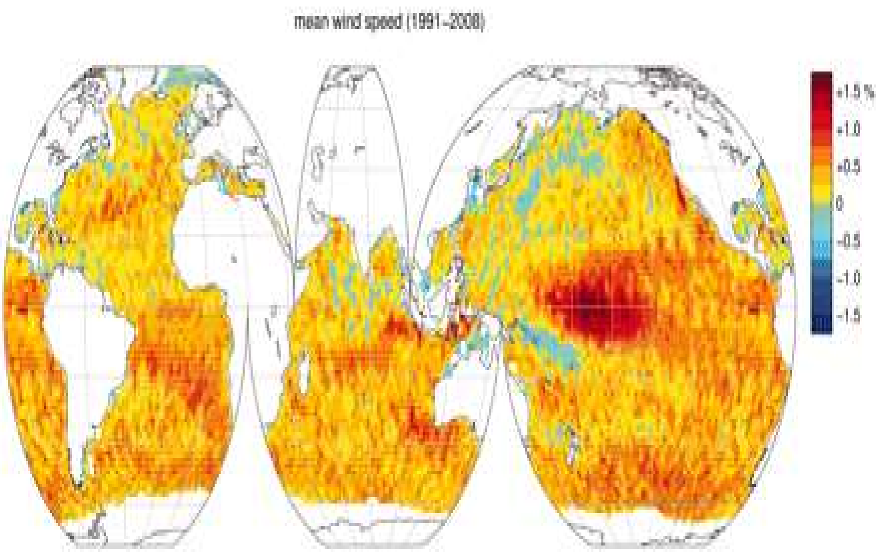
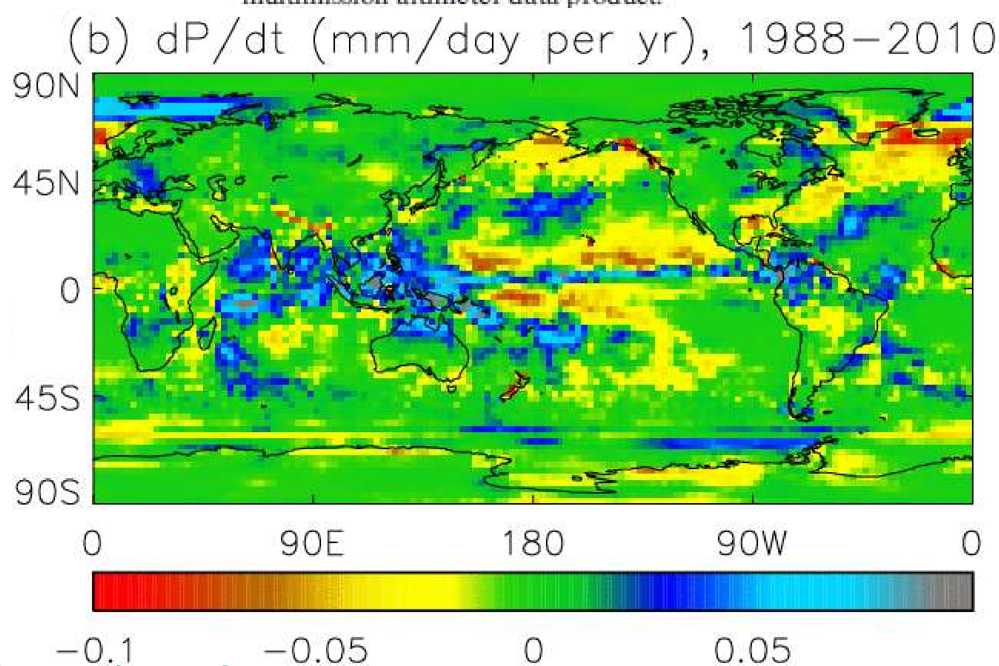


FIG. 1. The linear trend in satellite altimetry SSH for the period 1993–2009 based on the Aviso multimission altimeter data product.

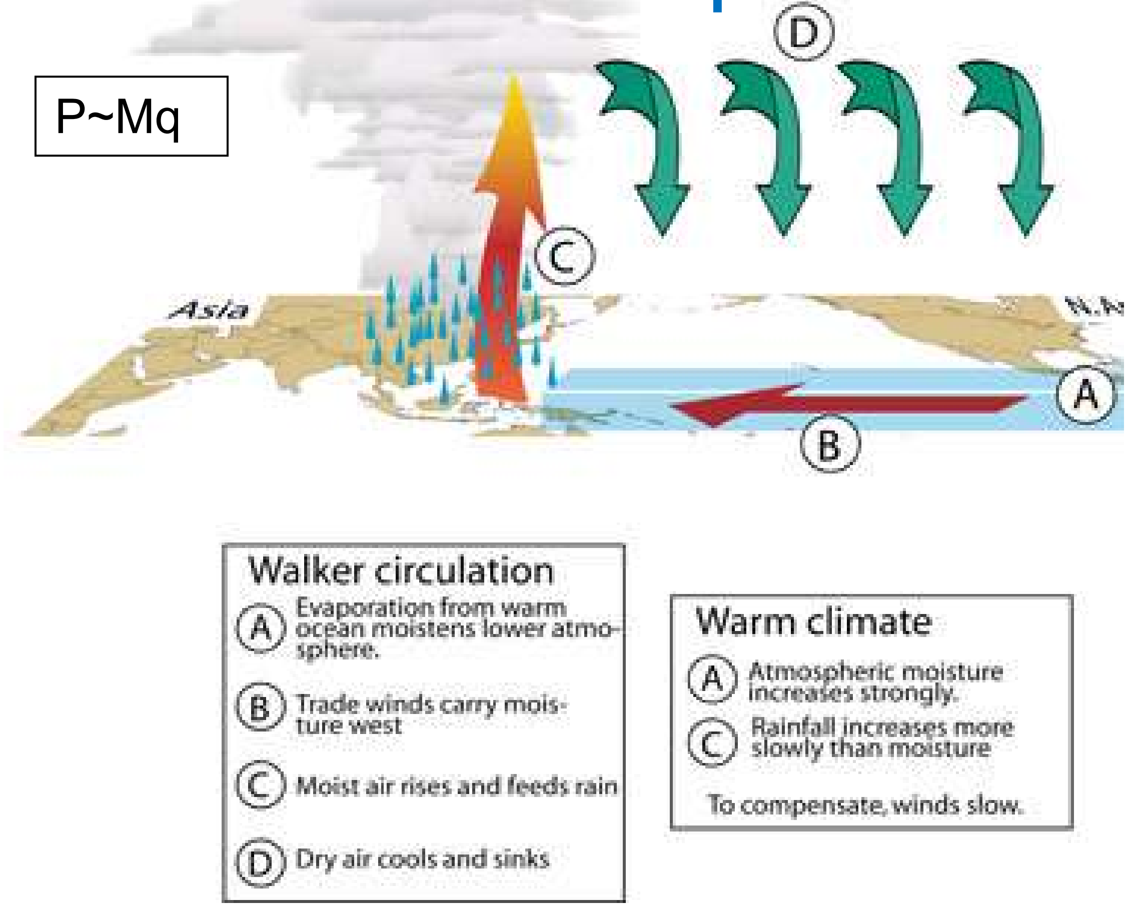




http://www.sciencemag.org/content/332/6028/451.full

Physical Basis: Circulation response

P~Mq



First argument:

P ~ Mq.

So if P constrained to rise more slowly than q, this implies reduced M

Second argument:

ω=Q/σ.

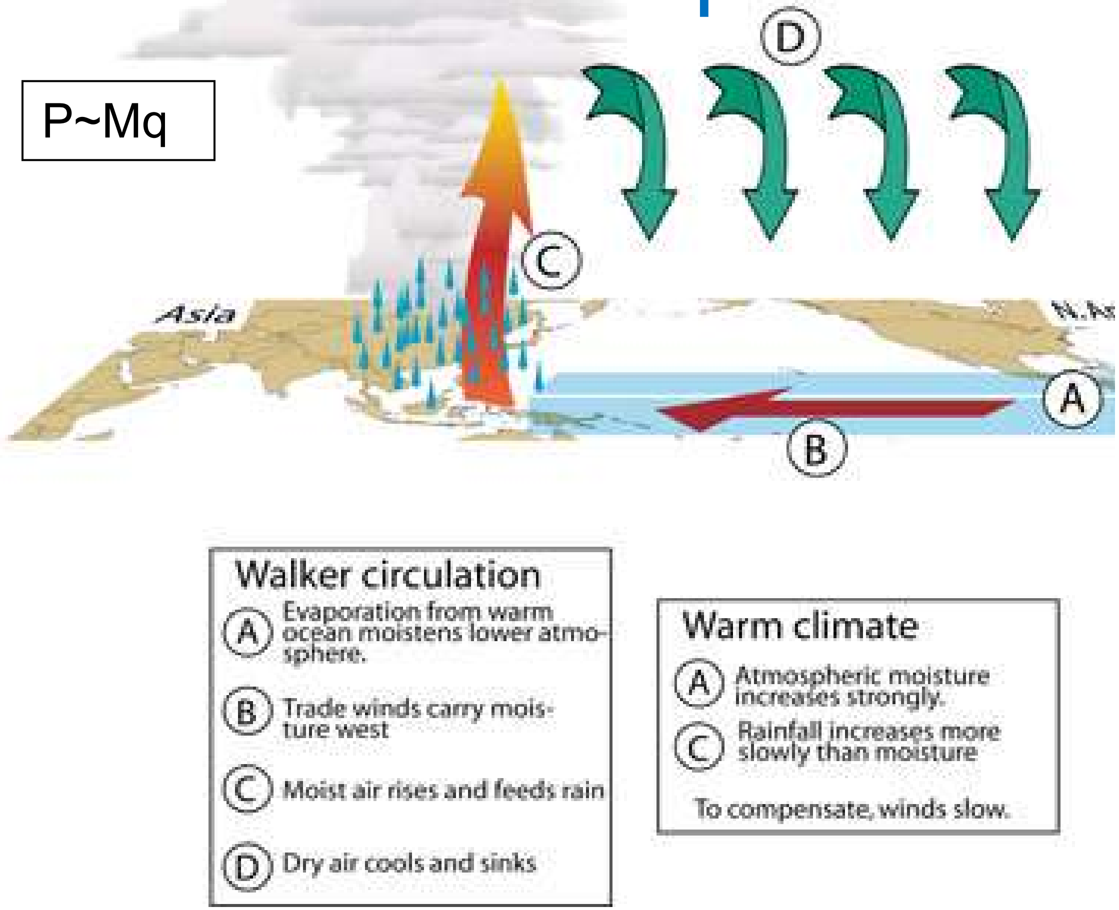
Subsidence (ω) induced by radiative cooling (Q) but the magnitude of ω depends on $(\Gamma_d - \Gamma)$ or static stability (σ).

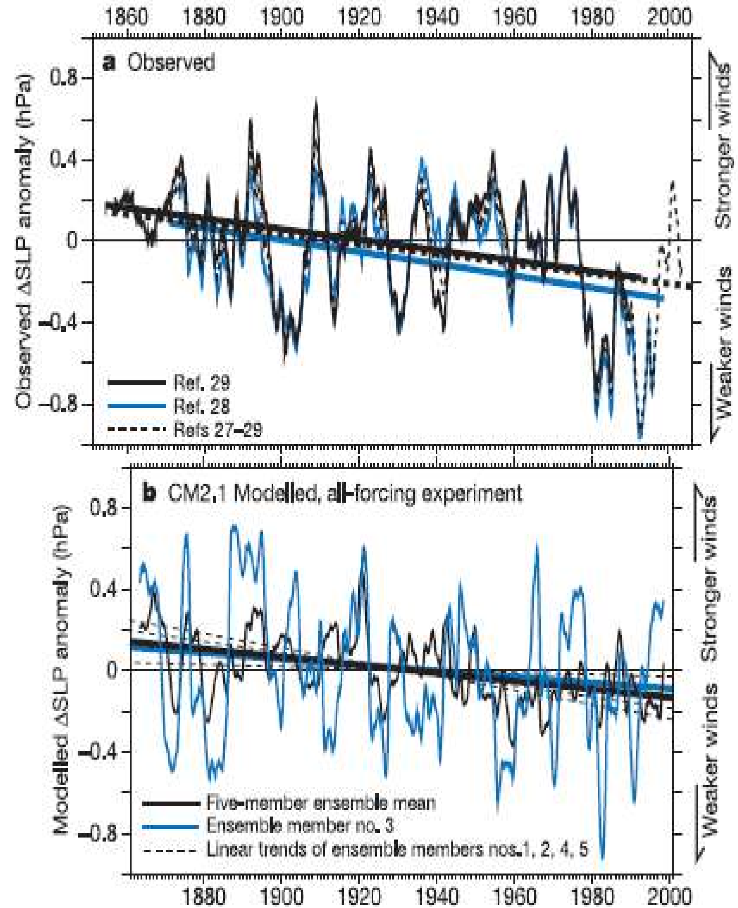
If Γ follows MALR → increased σ. This offsets Q effect on ω.

See Held & Soden (2006) and Zelinka & Hartmann (2010) JGR

Physical Basis: Circulation response

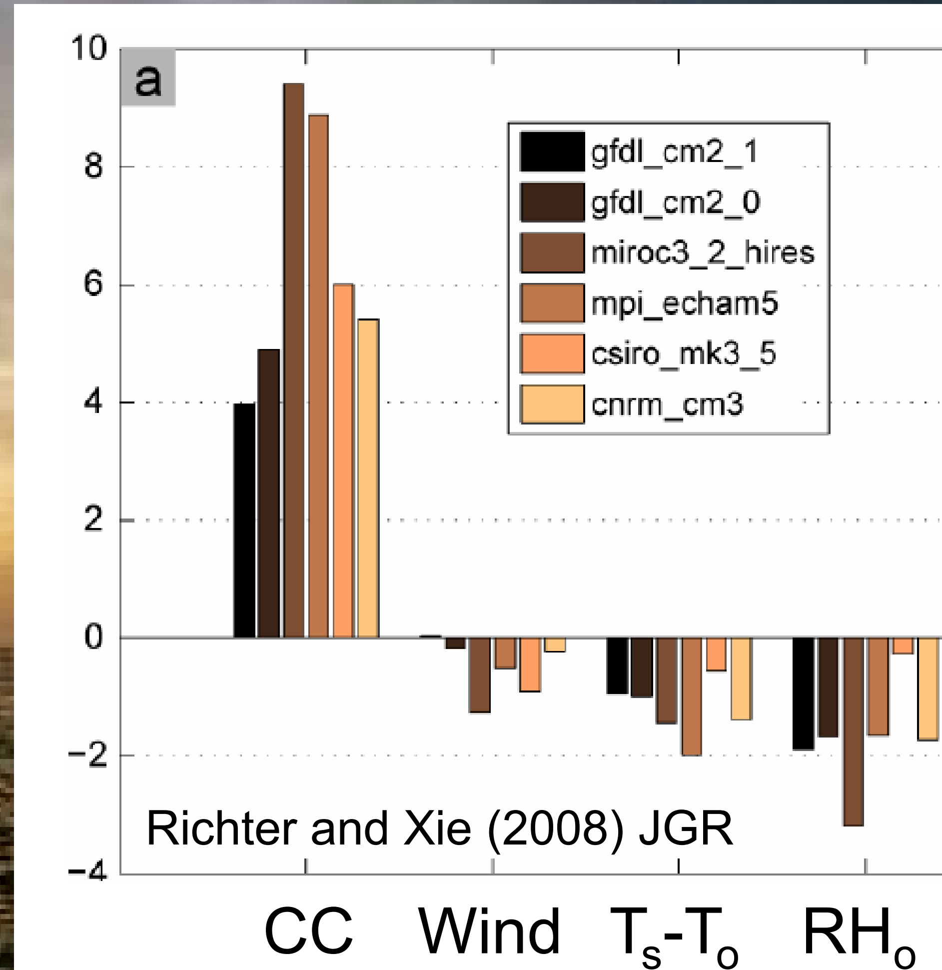
P~Mq





Models/observations achieve muted precipitation response by reducing strength of Walker circulation. Vecchi and Soden (2006) Nature

Evaporation

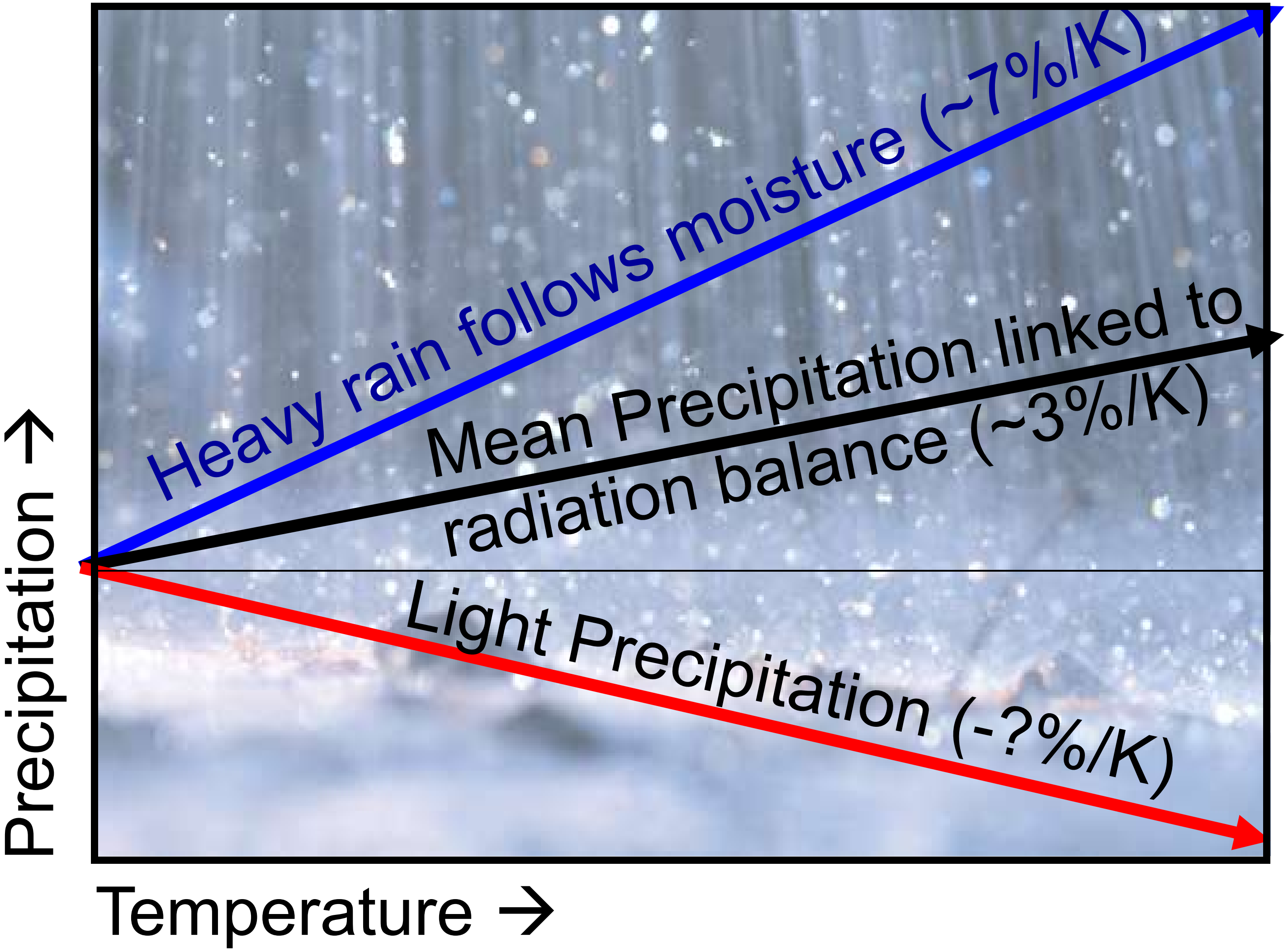


$$Q_E = L_v C_E \rho_a W (q_s - q_a)$$

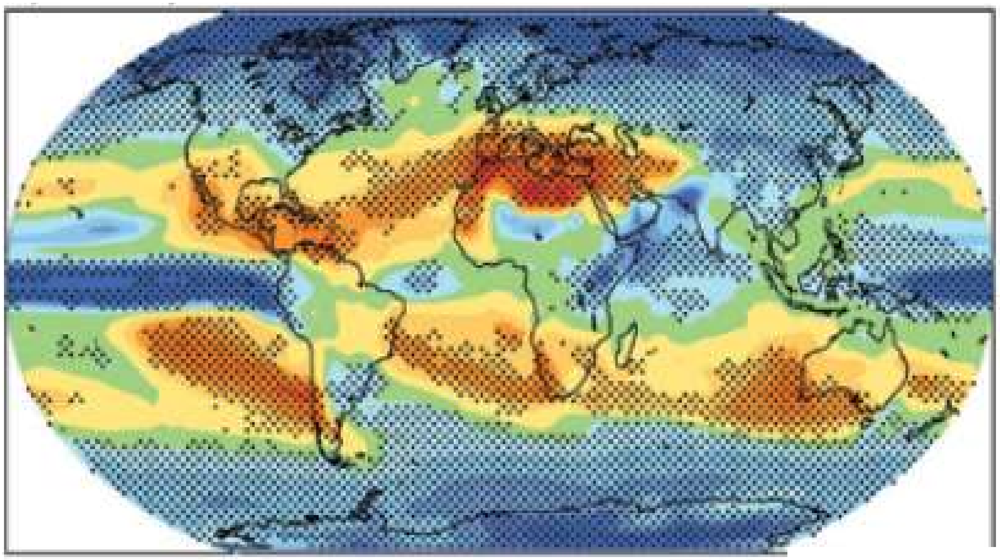
Muted Evaporation changes in models are explained by small changes in Boundary Layer:

1) declining wind stress
2) reduced surface temperature lapse rate (T_s-T_o)
3) increased surface relative humidity (RH_o)

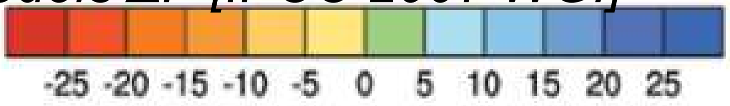
Contrasting precipitation response expected



The Rich Get Richer?



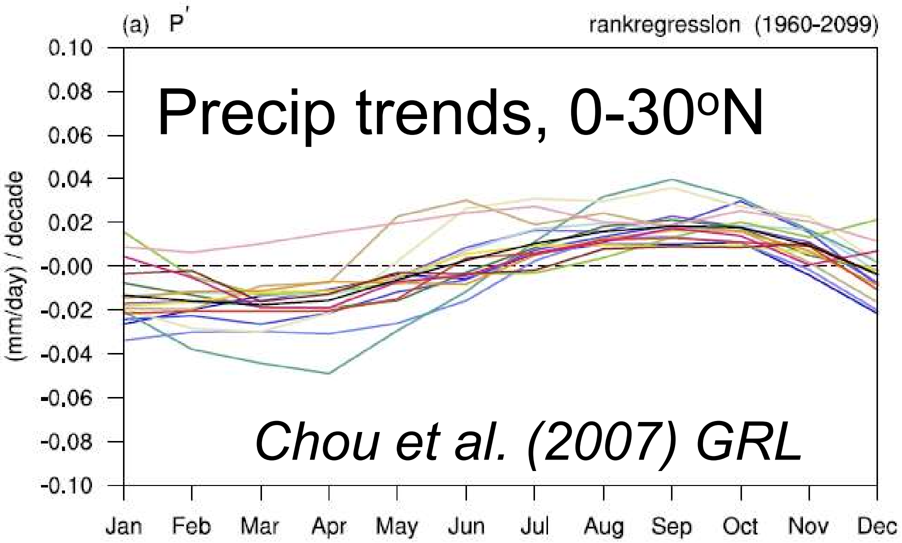
Models ΔP [IPCC 2007 WGI]



Is there a contrasting precipitation response in wet and dry regions?

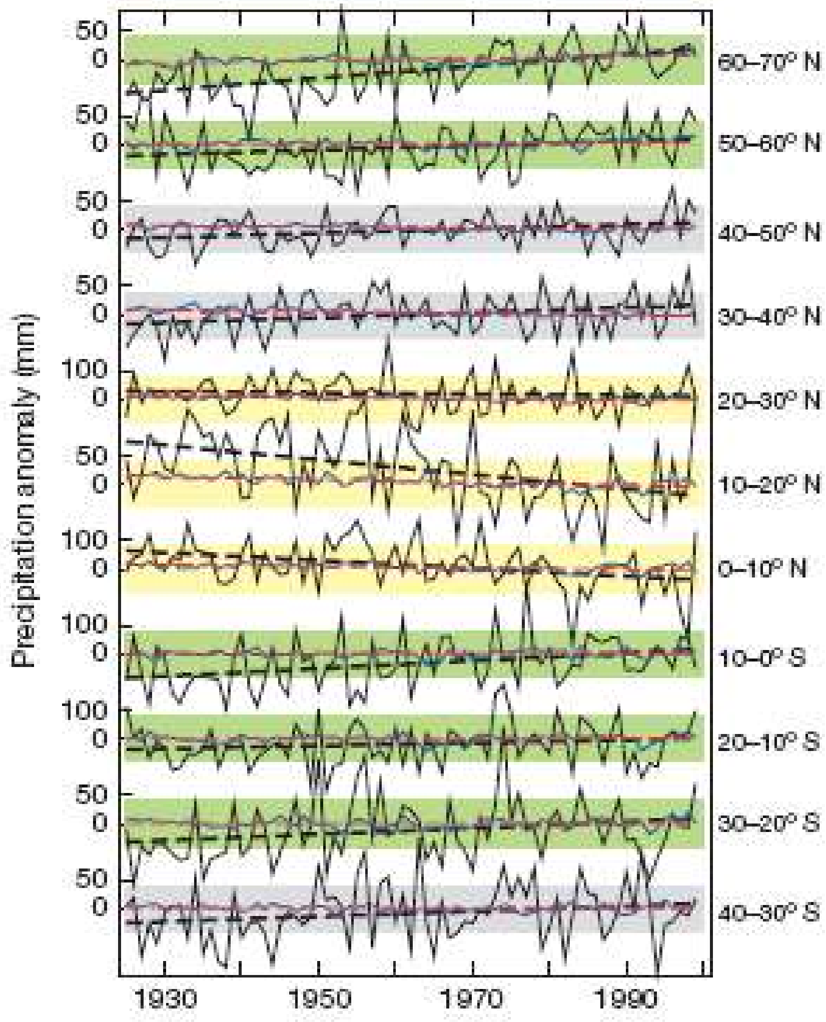
Rainy season: wetter

Dry season: drier



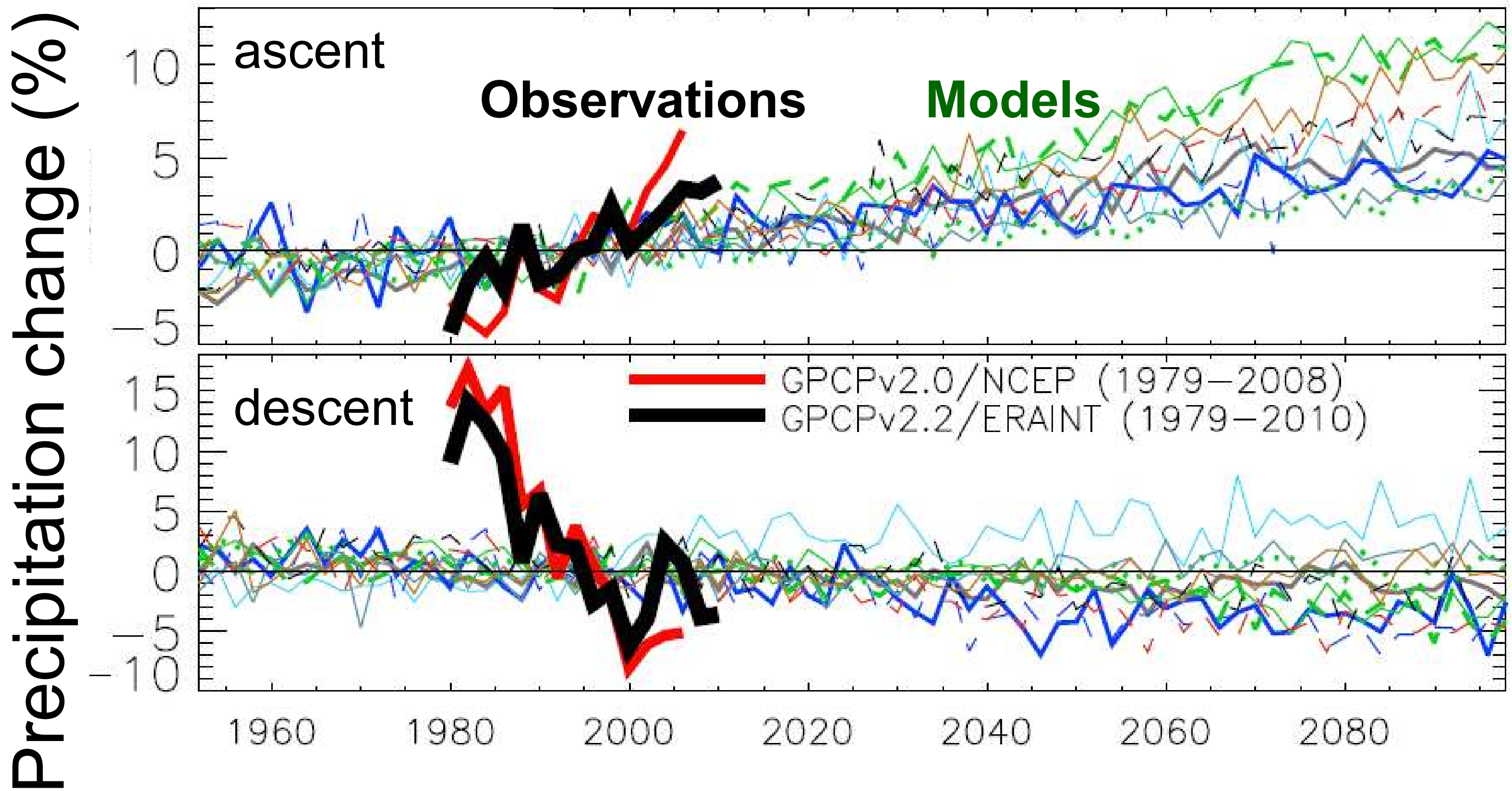
Chou et al. (2007) GRL

Detection of zonal trends



Zhang et al. 2007 Nature

Contrasting precipitation response in wet and dry regions of the tropical circulation

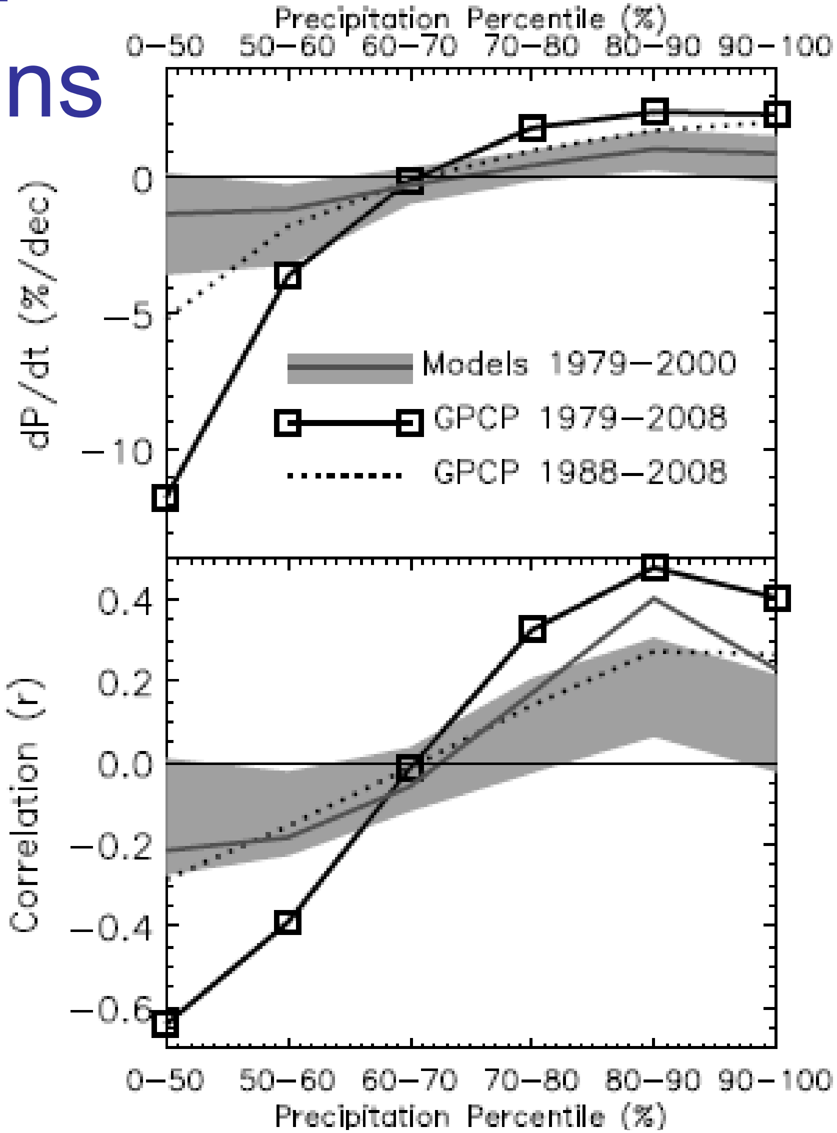


Sensitivity to reanalysis dataset used to define wet/dry regions

Updated from Allan and Soden (2007) GRL; Allan *et al.* (2010) Environ. Res. Lett.

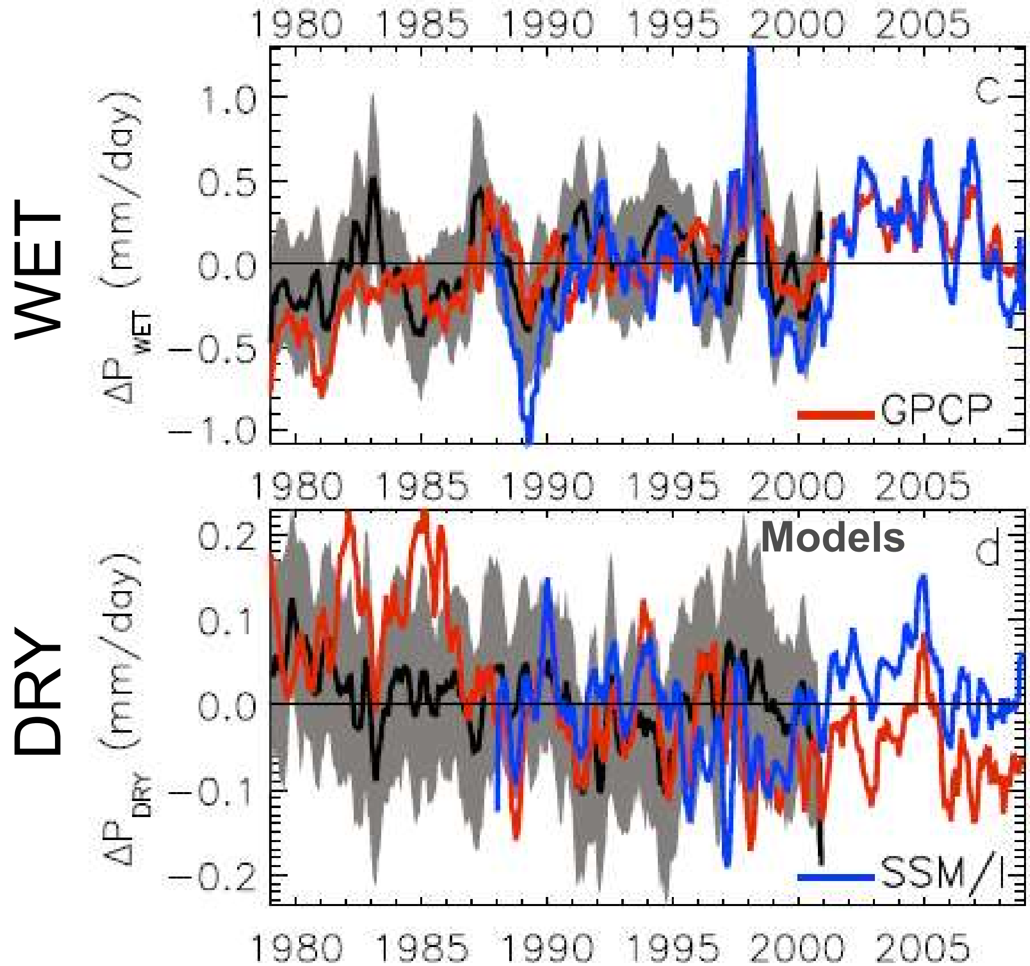
Avoid reanalyses in defining wet/dry regions

- Sample grid boxes:
  - 30% wettest
  - 70% driest
- Do wet/dry trends remain?



Allan et al. (2010) Environ. Res. Lett.

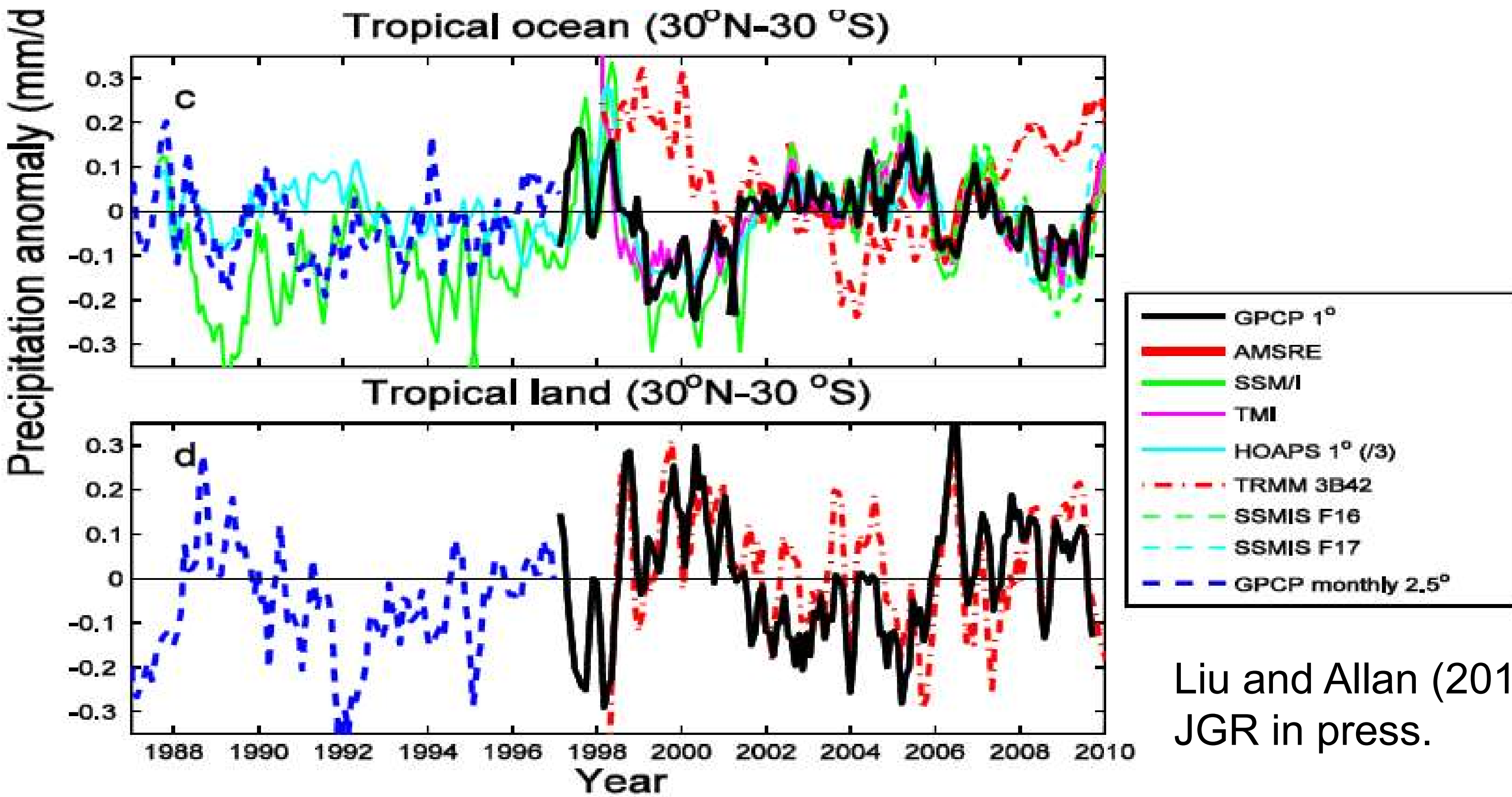
Current trends in wet/dry regions of tropical oceans



Allan et al. (2010) Environ. Res. Lett.

- Wet/dry trends remain
  - 1979-1987 GPCP record may be suspect for dry region
  - SSM/I dry region record: inhomogeneity 2000/01?
- GPCP trends 1988-2008
  - Wet: 1.8%/decade
  - Dry: -2.6%/decade
  - Upper range of model trend magnitudes

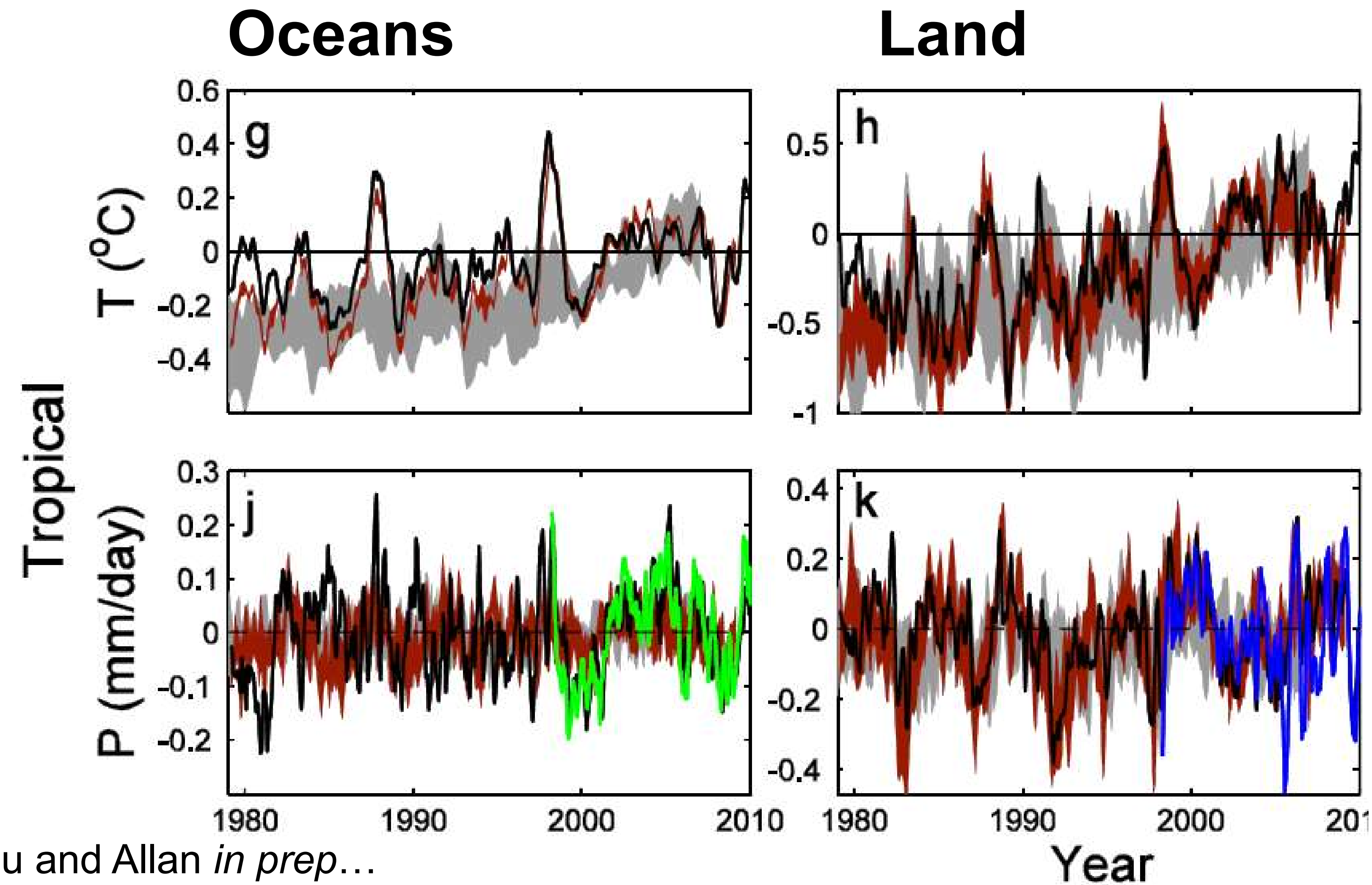
Exploiting satellite estimates of precipitation



Liu and Allan (2011) JGR in press.

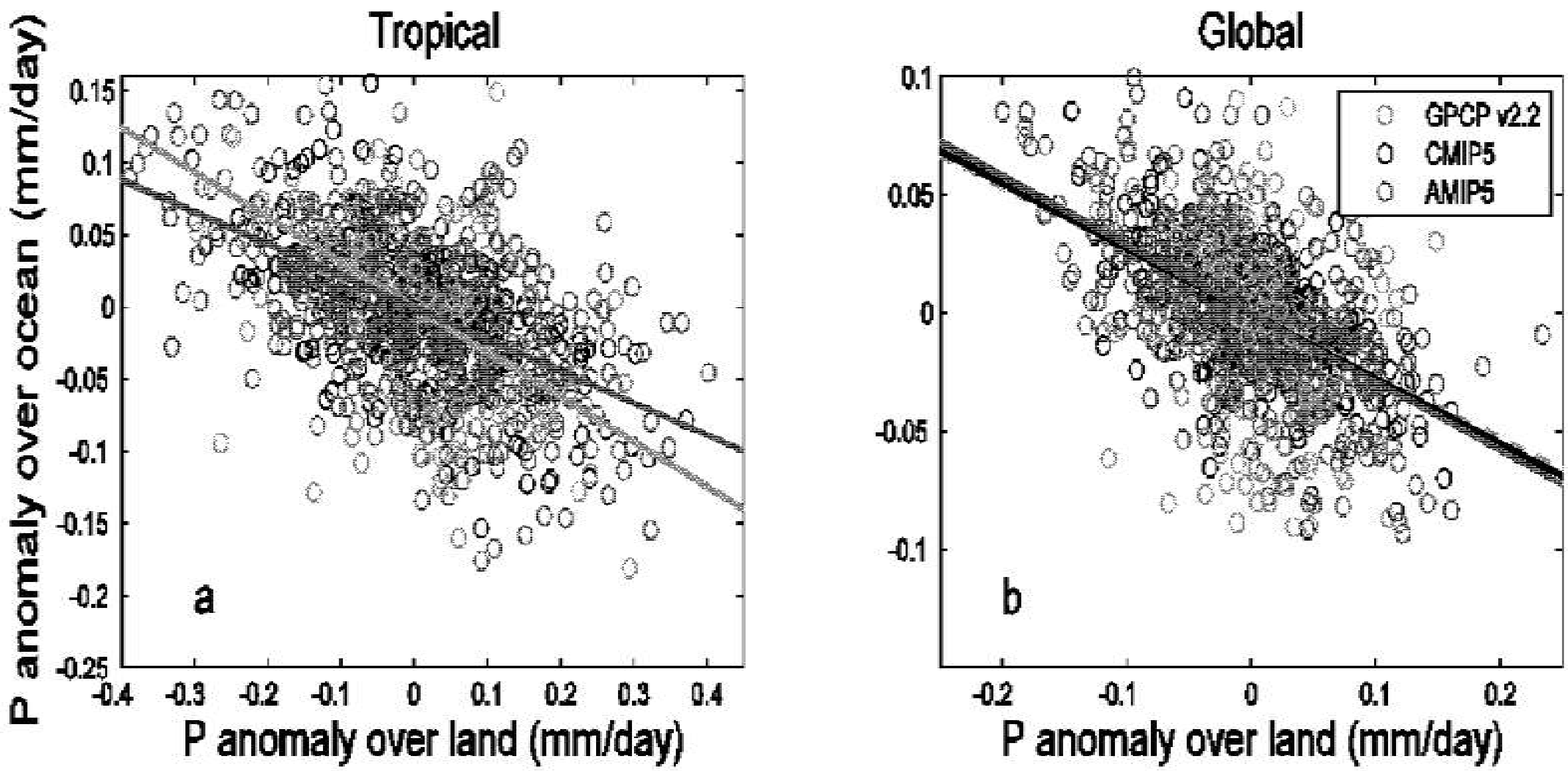
- HOAPS and TRMM 3B42 are outliers
- Strong sensitivity to ENSO

Current changes in tropical precipitation in CMIP5 models



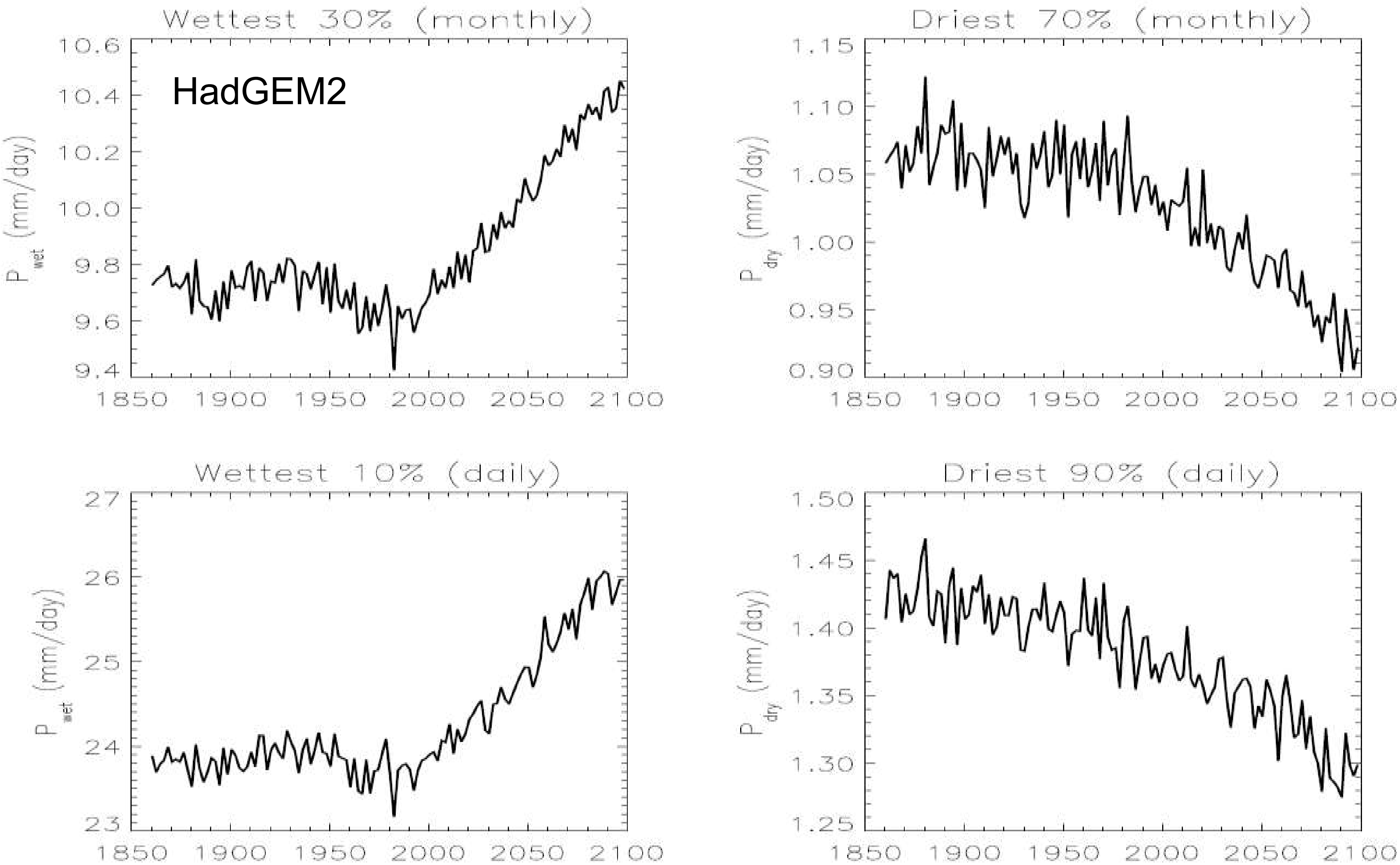
Liu and Allan *in prep*…

Contrasting land/ocean changes relate to ENSO



See also Gu et al. (2007) J Clim

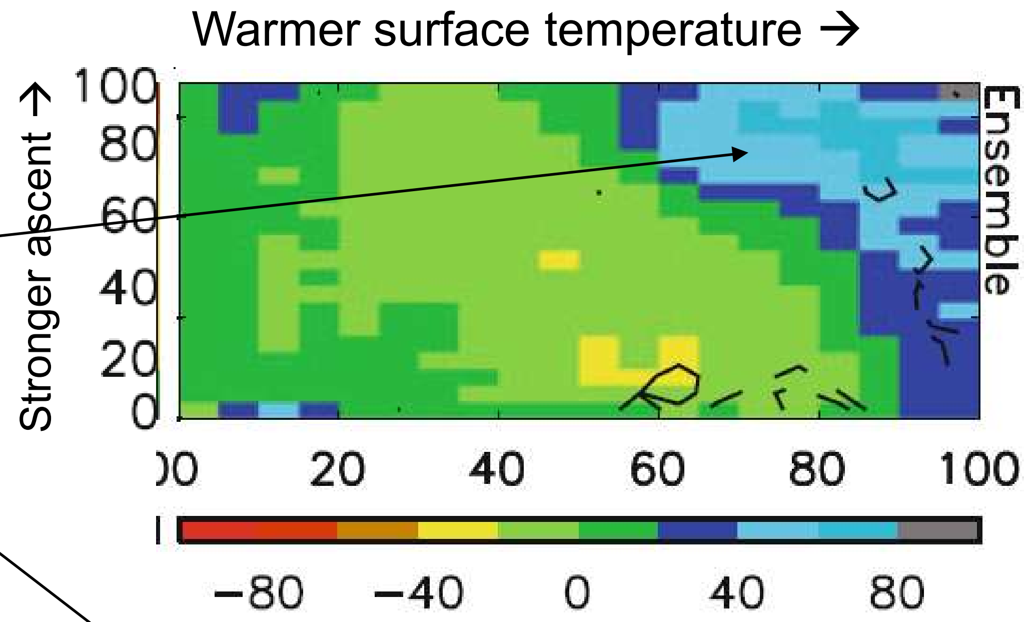
Projected changes in tropical precipitation (HadGEM2)

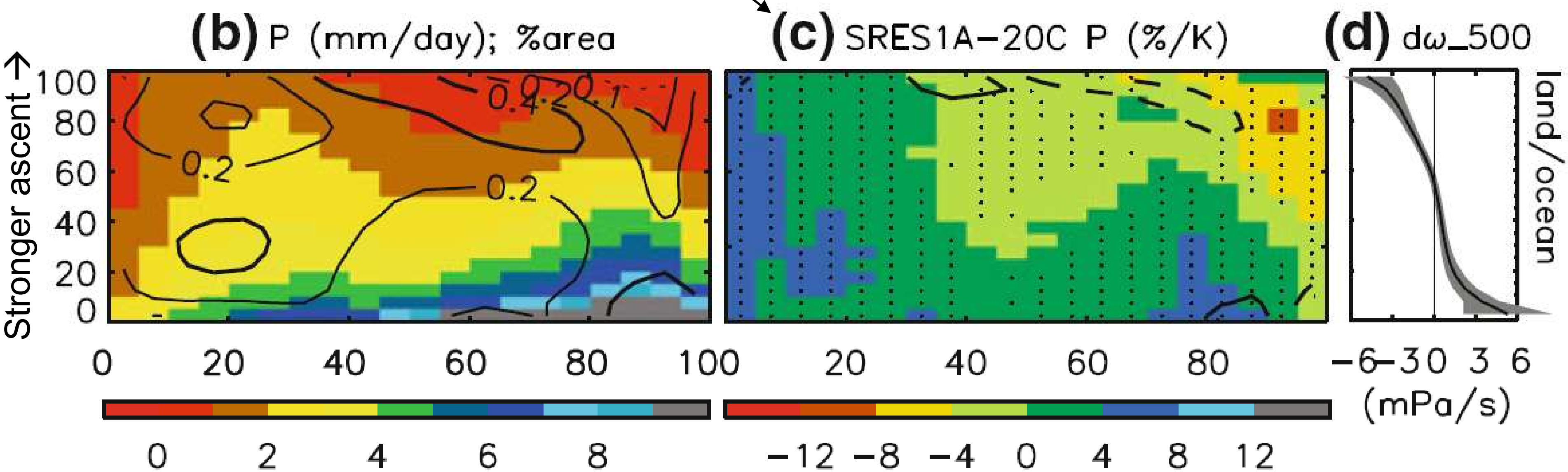


Precipitation bias and response binned by dynamical regime

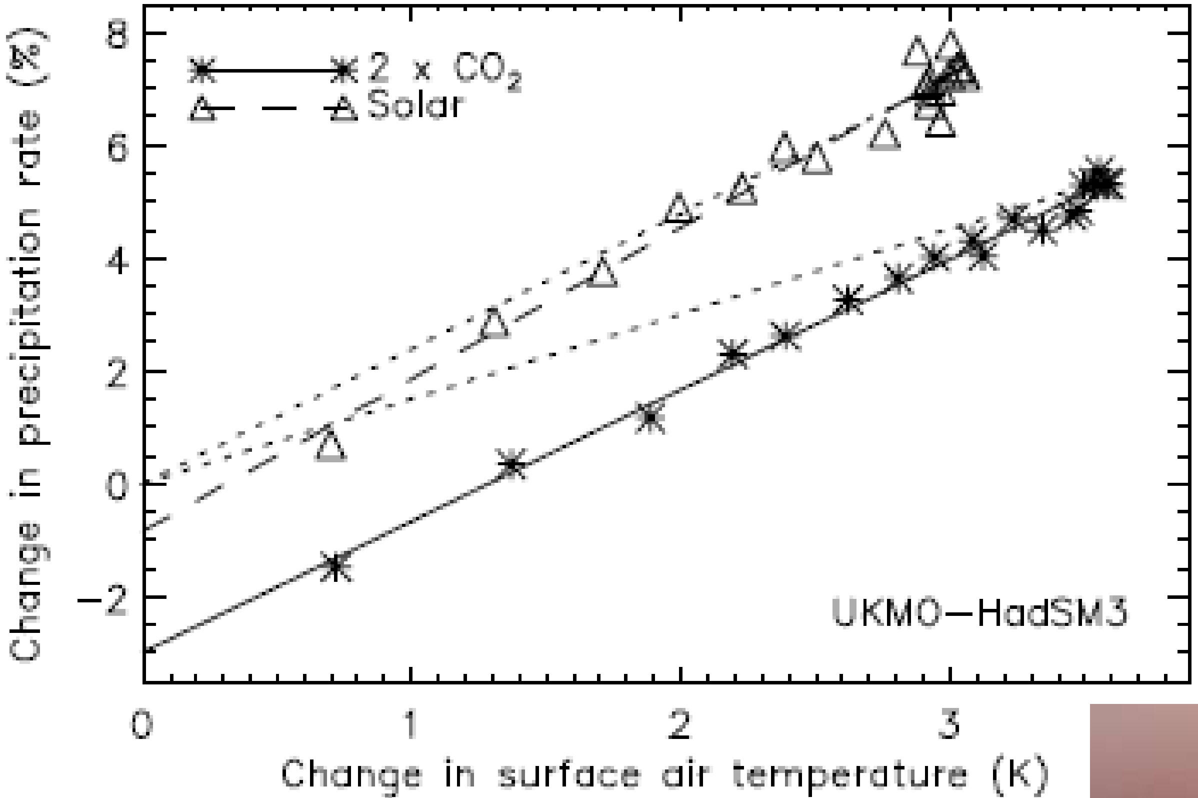
- Model biases in warm, dry regime
- Strong wet/dry fingerprint in model projections (below)

Allan (2012) Clim. Dyn.

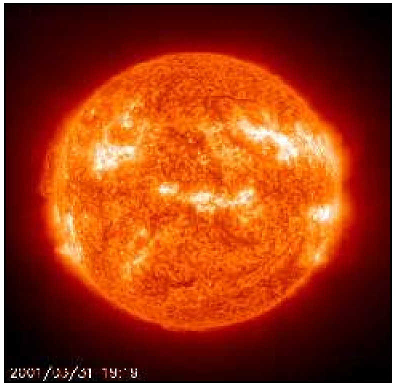




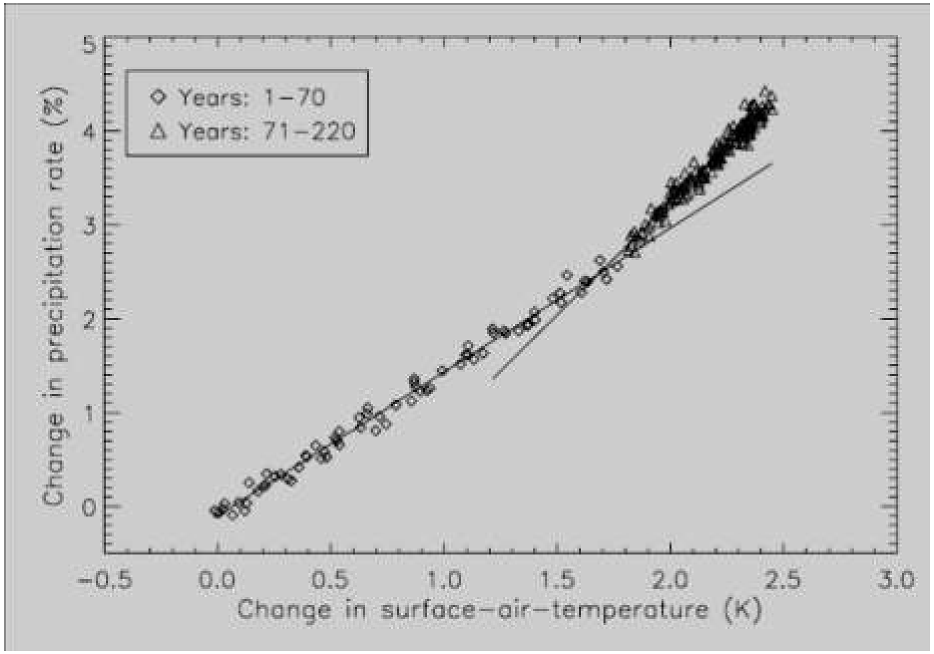
Transient responses



Andrews et al. (2009) J Climate

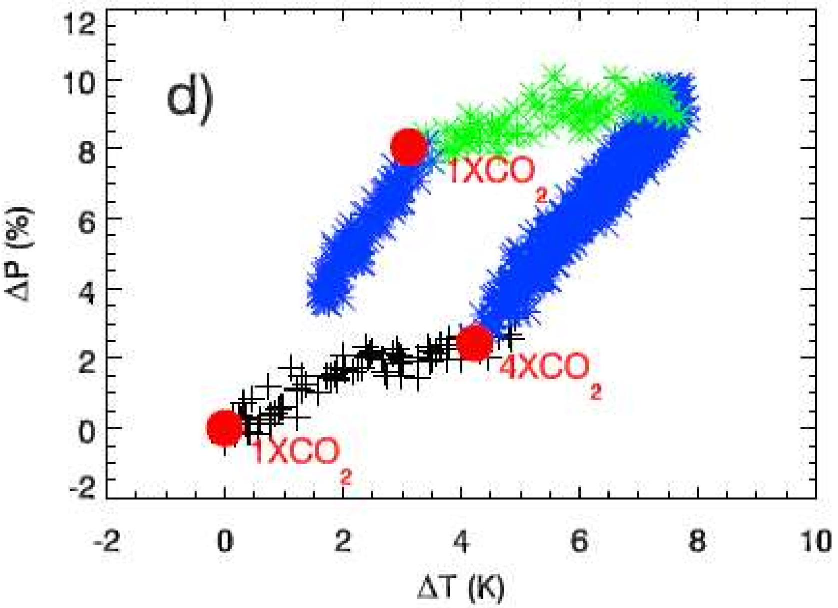


Transient responses



CMIP3 coupled model ensemble mean: Andrews et al. (2010) Environ. Res. Lett.

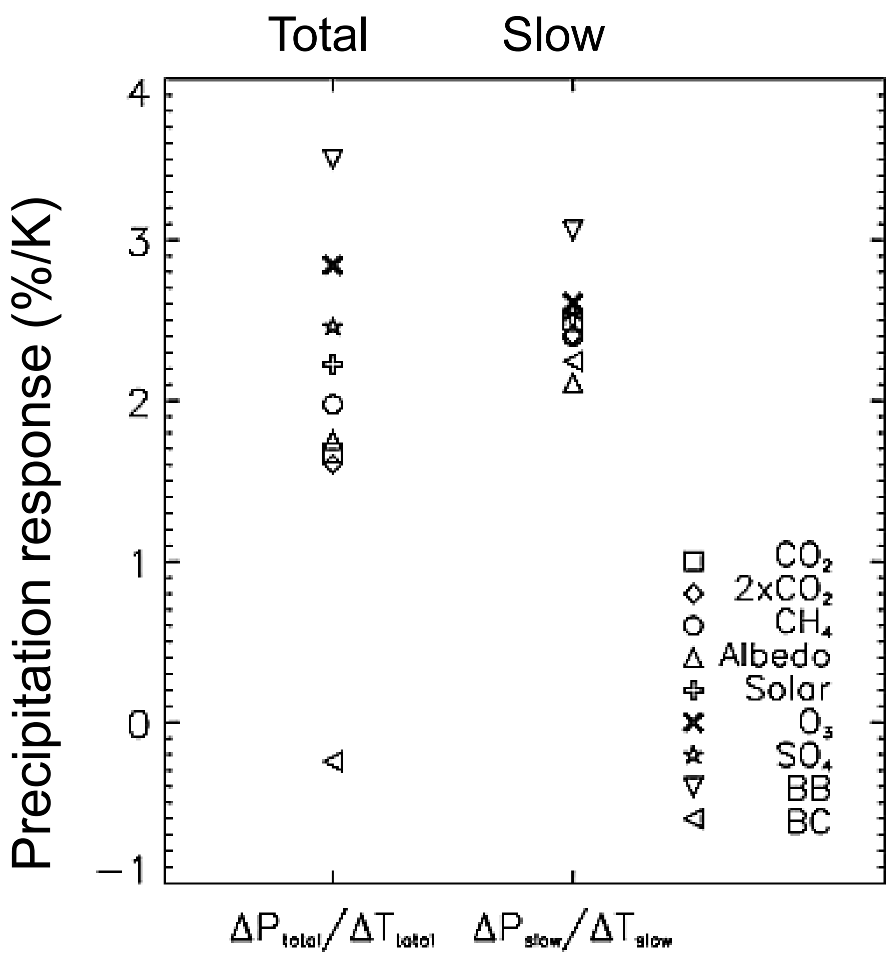
- CO_2 forcing experiments
- Initial precip response supressed by CO_2 forcing
- Stronger response after CO_2 rampdown



HadCM3: Wu et al. (2010) GRL

Degree of hysteresis determined by forcing related fast responses and linked to ocean heat uptake

Forcing related fast responses



Andrews et al. (2010) GRL

- Surface/Atmospheric forcing determines "fast" precipitation response
- Robust slow response to T
- Mechanisms described in Dong et al. (2009) J. Clim
- CO_2 physiological effect potentially substantial (Andrews et al. 2010 Clim. Dyn.; Dong et al. 2009 J. Clim)
- Hydrological Forcing:

  HF=kdT-dAA-dSH

  (Ming et al. 2010 GRL; also Andrews et al. 2010 GRL)

Conclusions

- **Robust Responses**
  - Low level moisture; clear-sky radiation
  - Mean and Intense rainfall
  - Contrasting wet/dry region responses
- **Less Robust/Discrepancies**
  - Observed precipitation response at upper end of model range?
  - Moisture at upper levels/over land and mean state
  - Inaccurate precipitation frequency/intensity distributions
  - Magnitude of change in precipitation from satellite datasets/models
- **Further work**
  - Decadal changes in global energy budget, aerosol forcing effects and cloud feedbacks: links to water cycle?
  - Separating forcing-related fast responses from slow SST response
  - Are regional changes in the water cycle, down to catchment scale, predictable?